

Smithsonian Astrophysical Observatory

FINAL REPORT

19 July 1991 - 28 February 1997

NAS8-39194

Hydrogen Maser Clock (HMC) Experiment

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HMC FINAL REPORT

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HYDROGEN MASER CLOCK (HMC) EXPERIMENT

1. The H-Maser Clock Experiment (HMC)

1.1 Status of the Flight Experiment

The HMC project was originally conceived to fly on a reflight of the European Space Agency (ESA) free flying platform, the European Recoverable Carrier (EURECA) that had been launched into space and recovered by NASA's Space Transportation System (STS). A Phase B study for operation of HMC as one of the twelve EURECA payload components was begun in July 1991, and completed a year later. Phase C/D of HMC began in August 1992 and continued into early 1995. At that time ESA decided not to re-fly EURECA, leaving HMC without access to space.

In April 1995, NASA began a study to look into the feasibility of flying HMC on the Russian space station, Mir. Feasibility was verified and NASA took the decision to continue the HMC program. The necessary design and hardware changes for attachment to, and operation with, the Mir vehicle were initiated in October 1995.

The requirement for a new space qualified highly precise event timer capable of time resolving the arrival time of laser pulses with a precision of 10 picoseconds was significant development in the HMC project. The development of this type of device was in progress at NASA until the advent of the Challenger tragedy, and at about that time, was abandoned. The development of the HMC laser pulse event timer was done at the Los Alamos National Laboratory using recently developed large-scale integrated timers developed for nuclear weapons tests to determine the spatial distribution of gamma rays, prior to being annihilated by the heat of the blast. This event timer is a significant addition to NASA space technology.

While the design of the HMC physics package did not require changes, and all of the electronics for EURECA were basically similar and usable on Mir, considerable effort went into designing a structure for housing HMC and attaching it to the exterior of the Shuttle docking module attached to Mir. A system for operating with and recharging batteries to continue power to HMC during Mir power shutdown and space equipment for data storage and transmission from Mir were added. Because of very limited command capability a great deal of automated program software was developed. The thermal design was revised to accommodate radiative heat transfer to space in place of the cooled pallet attachment system on Eureka. Design was completed and construction

was begun, of the mounting structure to support the HMC maser that met the dynamics requirements of the "get away special" structure in the Shuttle cargo bay. The HMC system thermal design to cope with direct exposure to space was completed. The payload adapter structure was also designed and its fabrication was initiated. A model of the HMC-Mir payload structure for neutral buoyancy testing at JSC along with the shipping and mechanical hoisting tackle for HMC was built, delivered and successfully tested and has been returned to SAO.

Problems encountered in the development of flight electronics caused a projected schedule slip of approximately six months. This situation was discussed with MSFC in June 1996. At the same time NASA's program with Mir required changes in the Shuttle accomodation manifest for other payload requirements. HMC was reassigned from STS-86 to STS-91. This provided schedule relief for HMC but caused a change in the planned sharing of Extra Vehicular Activities with another payload required HMC to go it alone and assume the entire cost of EVA. The estimated cost to complete was increased to include the sustaining effort required because of launch postponement.

Because of budget priorities and NASA's lack of a continuing need for a highly stable space qualified clock system, NASA decided not to provide the additional funding for HMC. In July of 1996 NASA Headquarters ordered MSFC to descope the program to allow only ground tests of the flight equipment.

To characterize the performance of the maser physics package, which had been made to function normally and had been installed in a vacuum tank in August 1996, a six month test and evaluation program was begun. The contract was finally closed out effective 2/28/97.

NASA has granted title of the flight hardware and of the associated HMC equipment and software to SAO.

While all the flight hardware was transferred by NASA to SAO, not all are presently in service. Where possible, the components not necessary for frequency stability testing of the Physics Package, have been placed in storage.

Prior to termination, the physics package of the HMC had completed performance verification tests, and as of this date (15 June 1997), continues operating at SAO in a vacuum tank. Most of the HMC flight support electronics have been fabricated and tested. At this time approximately 80% of the electronics are presently operating the physics package in a vacuum tank at SAO, and are now considered to be well-tested flight electronics.

Since the only realistic way to evaluate the behavior of a clock is to let it run and compare it with other clocks, we expect to continue operating the flight Physics Package till the end of 1997 or until a flight opportunity become available. The physics package will then be recharged with Hydrogen, its sorption pumps reactivated and made ready for its full four years of operation.

This final report for the H Maser Clock project summarizes the effort devoted to the development and testing of a Hydrogen maser clock system, over the period 19 July 1991 through 28 February 1997.

As will be evident from the content of this report, we continue to be optimistic about new opportunities to test the HMC space hardware and to perform experiments of both technological and scientific significance with it in space.

1.2 Status of Flight Hardware

As of August 1996, most of the HMC flight electronics were completed and testing had begun. The flight physics package was completed. Design of the HMC structural hardware and procurement of the basic structural hardware materials was done. Construction of the structure was in progress and was halted at the time of termination.

Procurement of the flight batteries, laser pulse arrival event timers, the Dedicated Experiment Processor (DEP) and the Data Storage Units (DSUs) was completed. Except for the batteries and the DSUs, these components are now in storage at SAO along with the Event Timer flight hardware. The DSUs and the GPS receiver were released to NASA for use on other payloads. Testing of the flight physics package continues in Maser Lab's vacuum tank.

2 The HMC Project and its Objectives

2.1 The Atomic Hydrogen Maser Oscillator

The atomic hydrogen maser (H maser) is the oscillator that achieves the highest level of stability of any frequency standard currently available. Its frequency stability is typically on the order of several parts in 10^{16} , corresponding to a time error of about 50 picoseconds in a day, or a second in 60 million years. This stability requires averaging over intervals as brief as one hour. In terrestrial applications, H masers are used by national standards laboratories for time keeping and metrology as a continuous, stable provider of a signal that is monitored and steered over long intervals by passive frequency discriminators.

H masers are indispensable for radio astronomy operation of Very Long Baseline Interferometry, a technique that provides the highest angular resolution of any form of astronomical measurement, equivalent to the width of a human hair as viewed from Boston to Los Angeles. H masers are also used for research in very high precision measurements of atomic interactions.

More than twenty H-masers have been built at SAO since the maser lab began at SAO in 1967. Masers built in the early 1970s are still in operation, are in use at radio astronomy sites in Germany, Sweden, Japan, Australia, and the United States; the NASA-JPL Deep Space Tracking Network uses SAO-built masers exclusively for its

spacecraft tracking frequency references. The U.S. Naval Observatory's Master Clock system employs SAO masers.

While the technology of the hydrogen maser has matured since its invention in 1960, its use in space has only begun. The first space borne maser, which was operated in the 1976 GP-A Gravitational Redshift Test¹, was designed for one year of continuous testing operations prior to its launch into a near-vertical two-hour flight. The maser performed well and the mission confirmed the Einstein Equivalence Principle, the cornerstone of his General Theory of Relativity, at a level of 0.01 %, the best results to date.

The exceptional frequency stability of hydrogen masers make possible many present and future applications in space. The stability of the maser was the key to the measurement capability of the GP-A experiment could permit substantially improved tests of relativity and gravitation in a close approach solar probe^{2,3}. Space borne H-masers have been recommended for use in improved navigation systems such as the Global Positioning System⁴. In the early 1980s NASA supported development of an H maser to be operated from the Shuttle as a "traveling clock" for very high precision worldwide time transfer⁵, and as local oscillators for the next generation of space-based radio telescopes, interconnected by multi link microwave Doppler-canceling systems, operating as Very Long Baseline Interferometers⁶. Arrays of several of these clock-equipped space telescopes, interconnected with multi link Doppler canceling systems⁷ make possible comparison between an inertial frame defined by VLBI positions of distant matter and inertial frames defined by the local velocity of light⁸. Widely separated clocks interconnected with multi link microwave systems would enable detection of very low frequency pulsed gravitational radiation.^{9,10,11,12,13} Another clear application for the H maser is in the International Space Station, where it would serve as an onboard utility for extremely high precision timing, in addition to serving external applications such as time transfer.

2. 2 HMC Experiment Objectives

This section reviews the objectives of the HMC project for evaluation the performance of the space maser and discusses use of a space maser in performing very high precision intercontinental time synchronization and time transfer.

2.2.1 Evaluation of the HMC capability in the Space Environment

The principal objective of the HMC program was to evaluate the performance of the SAO hydrogen maser clock in space. This evaluation involves the following:

- A) Measurement of the frequency stability of the space borne maser with respect to a ground based H-Maser by high precision pulsed laser-time comparisons.
- B) Observation of the maser's operation by monitoring and controlling, through telemetry and telecommand, a variety of parameters associated with the maser's functioning, including:

1. Environmental parameters, such as ambient temperature and magnetic field.
 2. Parameters associated with the maser's performance as an oscillator, such as signal level and oscillation line Q.
 3. Parameters associated with the maser's internal operation, including the temperature control system's temperatures and powers, hydrogen flux density and dissociation efficiency, and vacuum system pressure.
- C) Determination from these measurements, (i) of the space maser's frequency stability over the duration of the mission, and (ii) of the effect of ambient conditions and the maser's internal systems on the maser's long-term frequency performance.

2.2.2 Demonstration of High Precision Global Time Synchronization.

Because Mir's orbital inclination is 51.6° , at least eleven or more laser tracking stations¹⁴ are within sight of the HMC system with which comparisons of absolute time could be made because of the extremely high stability of the flying HMC reference clocks between laser contacts. Approval was obtained from the Russian Space Agency and the Russian Bureau of Standards, VNIIFTRI, to compare time with their laser station at Mendeleevo. (See letter from Prof. V. Tatarenkov in Appendix 1)

3 HMC Project Technology

3.1 The Atomic Hydrogen Maser

The atomic hydrogen maser (H-maser) is an oscillator powered by microwave energy resulting from quantum transitions from an upper hyperfine energy level of atomic hydrogen to a lower level. In the maser, a beam of H-atoms, selected to be in the upper level, is streamed into a specially coated storage bulb where they bounce around for about 1 second before emerging. During their time in the bulb, the atoms coherently release their energy to a cavity resonator that is tuned to the transition frequency. The longer the time of storage, the more frequency selective is the transition process and hence, the more stable the output frequency. Figure 1 is a schematic diagram of the hydrogen maser with the energy level diagram of atomic hydrogen.

To obtain atomic hydrogen from molecular hydrogen, the gas at low pressure is fed to a radio-frequency dissociator, a small glass vessel where a strong radio frequency circuit excites the hydrogen to produce a glow discharge where the molecules are bombarded with electrons and break apart into atoms. The atoms are formed into a narrow beam and aimed down the axis of a six pole state selecting magnet. The magnetic fields near the poles are extremely strong, and by symmetry, the field along the axis of the

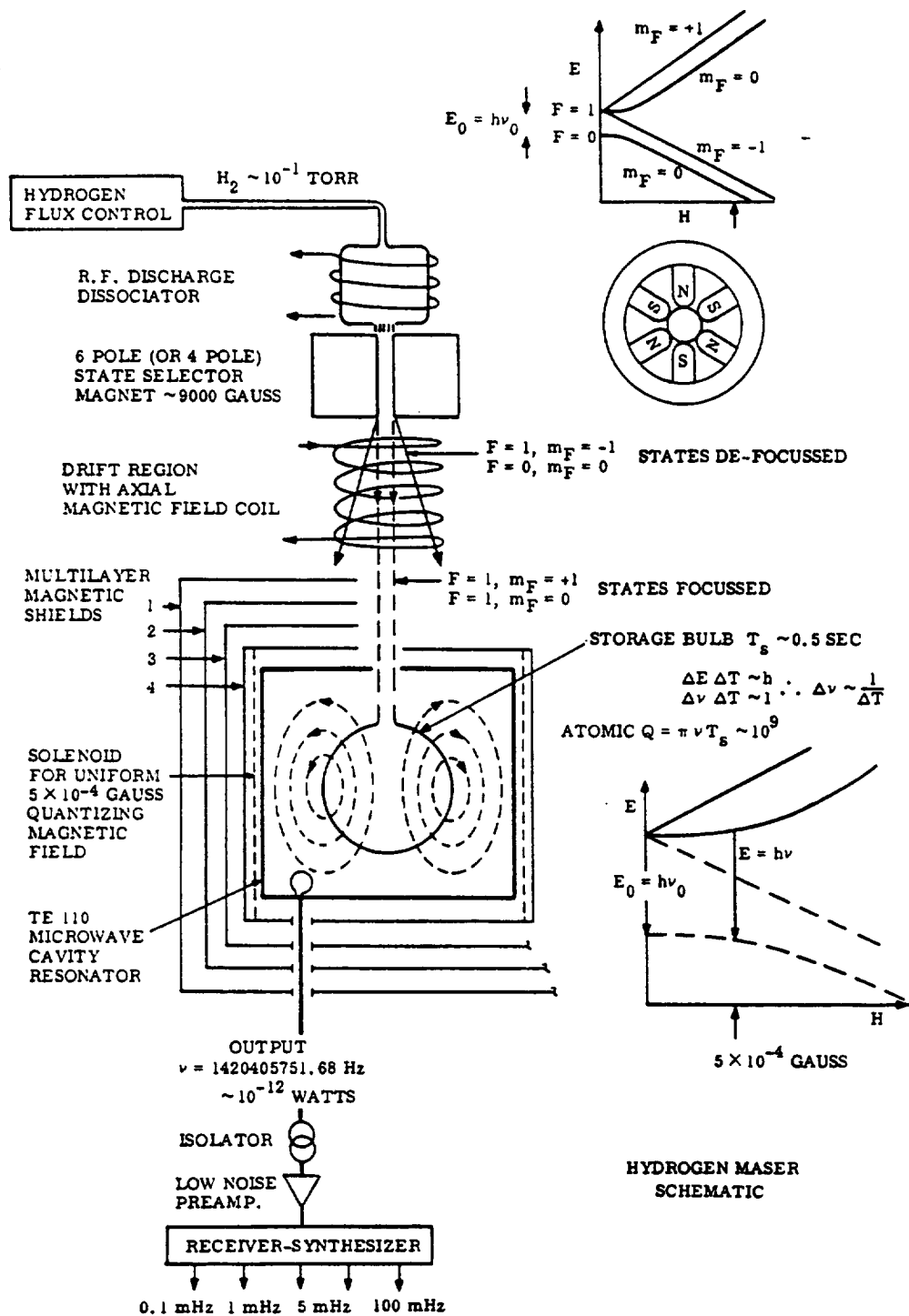


Figure 1
 Schematic Diagram of the Hydrogen Maser with the Energy Level Diagram of Atomic Hydrogen

magnet is zero. The magnetic gradient in the six pole magnet acts to deflect the atomic hydrogen in a radial direction. The $F = 1$ state atoms in the $m_F = +1$ and 0 sublevels head toward weak fields near the axis, while the $m_F = -1$ and the $F = 0$ state atoms are deflected outwards toward high fields. The upper state atoms enter a specially coated storage bulb inside a resonant cavity where the stored atoms interact with the microwave magnetic field and are stimulated to release their energy phase-coherently with the field in the resonator, thus sustaining the oscillation. The average time of occupancy in the bulb is about 1 second and depends on the design of the bulb collimator. The atoms, after making a large number of collisions with the walls of the bulb, leave through same opening they entered. Expended hydrogen is removed by passive sorption cartridges; other gases are removed by a small ion pump.

As is seen in the energy level diagram in Figure 1, there is a quadratic dependence of the maser frequency on magnetic field. For best immunity this means that we should operate as low fields as practical. We choose to operate at 0.5 milliGauss. To maintain immunity at a level $\Delta f/f < 1 \times 10^{-15}$ from magnetically induced frequency variations of 0.5 Gauss, we require attenuation of external fields by a factor of several million. This is done by a combination of four layers of passive magnetic shields and active magnetic compensation by sensing the field within the outer most layer and canceling it with a servo controlled current to coils..

Even though the linewidth of the atomic transition is small, ~ 1 Hz, mistuning of the cavity resonator can "pull" the output frequency in the ratio of the line width to the cavity resonance line width. This ratio is about 10^5 . To maintain $\Delta f/f < 1 \times 10^{-15}$, we require the resonance frequency to be stable at a level of about 0.1 Hz. To accomplish this, the resonator is made from a very dimensionally stable glass-ceramic material¹⁵ having an extremely low coefficient of thermal expansion whose temperature is maintained within a few tenths of a milliKelvin.

The frequency stability of the maser results from the long storage time during which the atoms phase coherently release their energy to the cavity resonator. As in other atomic standards, the longer the storage time, the narrower the line width of the atomic response; in this case release of power as an output signal. Power at a level of 10^{-10} watts is coupled from the resonator, amplified and led to a receiver/frequency synthesizer where the 1,420,405,751.7864 Hz phase-locks a 100 MHz crystal oscillator. The synthesizer frequency is adjustable at the 10^{-17} level in $\Delta f/f$.

The atomic hydrogen maser is the most stable frequency standard currently available for measurement intervals ranging from second to weeks. Its outstandingly predictable frequency drift makes possible the generation of timing signals of unprecedented accuracy for intervals between one day and several weeks. Figure 2 shows the typical stability of atomic hydrogen masers that have been in production at SAO since 1977.

The performance goal of the HMC project is to demonstrate, in space operations, the stability shown in Figure 3 (Figure 1 from the from the HMC Contract End Item

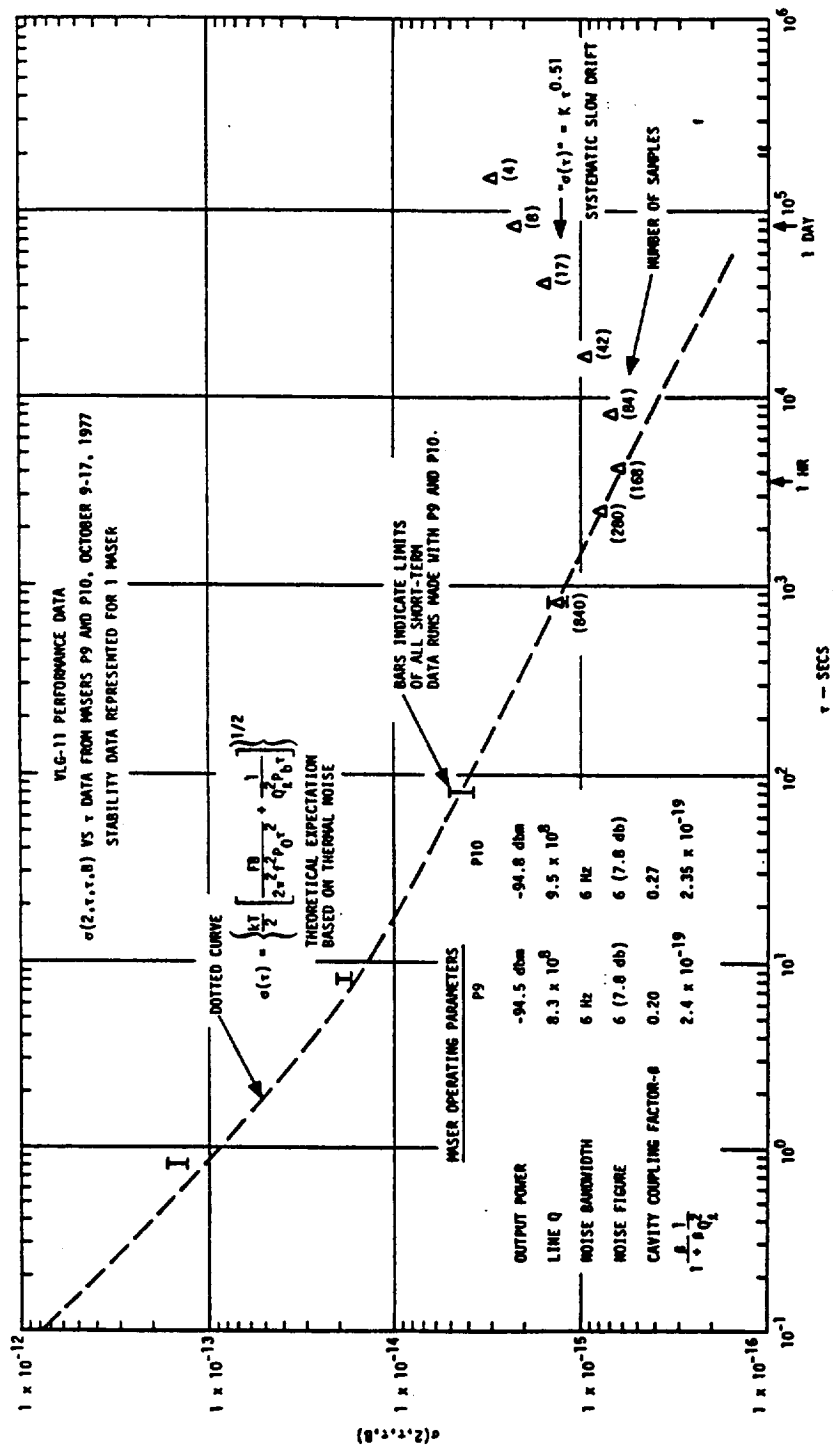


Figure 2
 Frequency Stability of SAO Atomic Hydrogen Masers

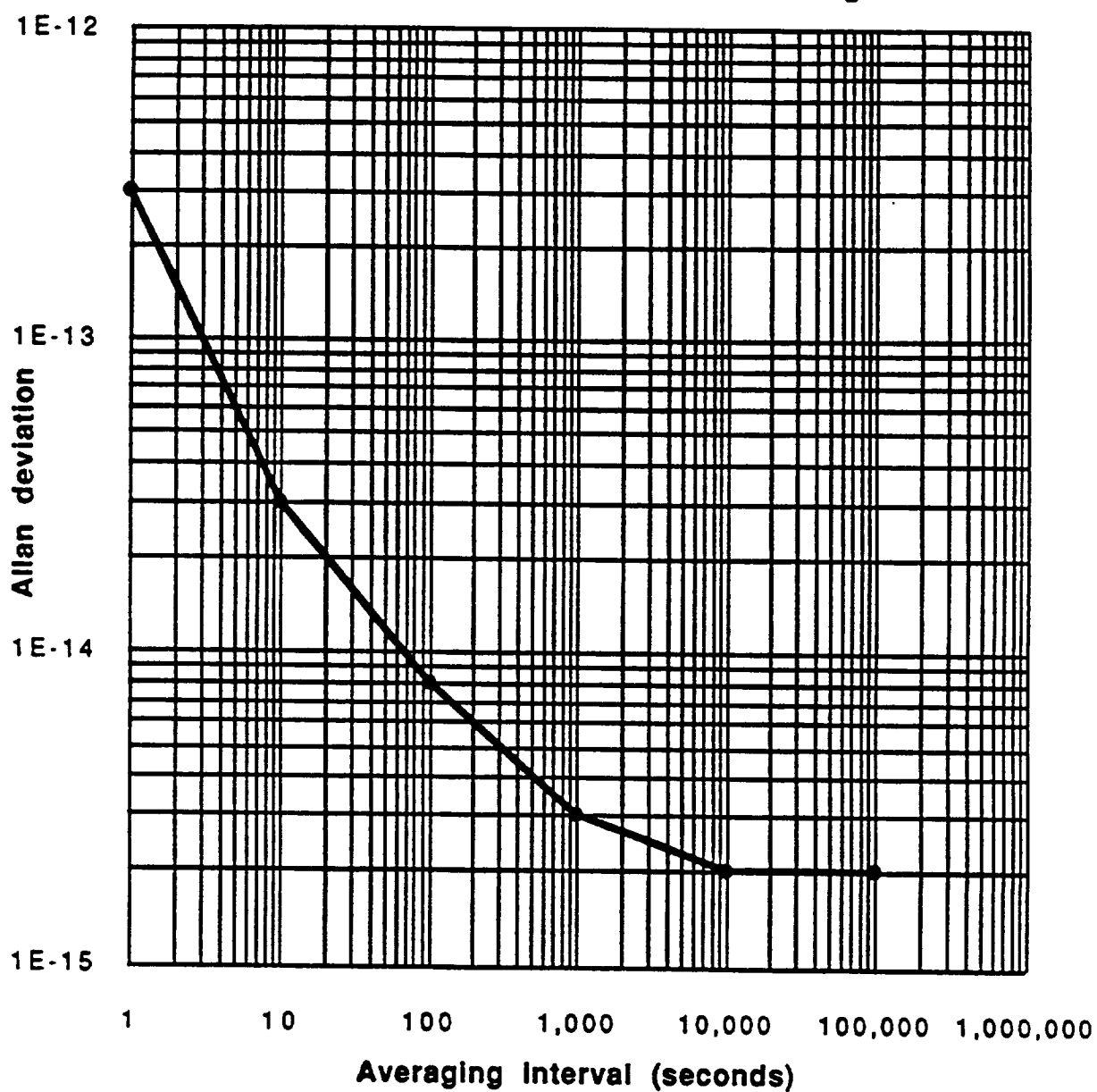


Figure 3
Frequency Stability requirement from the from the HMC Contract End Item
Specification

Specification.) A later figure in this report shows that the frequency stability requirements have been amply met.

3.2 High Precision Time Transfer System

Time transfer measurements were to be made as follows. The HMC payload attached to the Mir docking module is equipped with an array of corner-cube reflectors and a laser pulse detector operating an event timer capable of resolving the arrival time of a laser pulse within 10 picosecond resolution in terms of a time scale operated by the space maser clock. The earth station laser transmits a pulse part of which is reflected back to earth and detected at earth. The time delay between transmitted and received pulses is recorded at the station. The time (or more properly the epoch) of the pulse transmission relative to the station clock is also recorded. The laser pulse received at the spacecraft triggers a photo detector co-located with the reflector which sends an electrical pulse to the event timer, which records a time reading in terms of the on-board maser clock time scale. This arrival time is recorded for subsequent telemetry to earth. Figure 4 shows an overview of the HMC experiment time transfer system and a block diagram of its major components.

Evaluation of the space maser's frequency stability was to be done by means of pulsed laser time comparisons with the laser-tracking station at the Goddard Space Flight Center in Greenbelt Maryland, which has a high precision time link with the US Naval Observatory in Washington DC. A reference frequency standard supplied by SAO was to provide a high stability frequency reference. Repeated high precision time comparisons would allow a comparison between the rate of the space clock and the rate of the earth clock.

3.2.1 Precision of the Time Transfer Process

Figure 5 shows a schematic light-time diagram for the time comparison process. The laser station data and the space-clock data are processed as follows: The times of laser transmission are compared with the times of reception at the spacecraft. One-half of the round-trip time at the laser station is subtracted from the arrival time at the spacecraft to correct for the propagation interval. The space borne clock time must be corrected for relativistic and gravitational effects; this correction requires a knowledge of the position and velocity of the spacecraft between timing measurements by the laser stations.

For an error contribution of 1 part in 10^6 in the predicted red shift correction, tracking at the 50 cm level in altitude is required. For a comparable fractional error in the prediction of the second-order Doppler effect correction, determination of relative velocity at the 3.8 mm/sec is required. (While this sounds difficult, we should remember that 3.8 mm/sec amounts to an along track error of 20.5 meters over every 90 minute orbit.) This accuracy is available with the space borne GPS receiver built for HMC by the Jet Propulsion Laboratory.

Depending on the weather at the laser station, we could expect as many as four periods of laser contact each day of up to four minutes duration. With laser pulse rates of at least eight per second we can expect to accumulate about 1800 timing data entries for

each pass, with precision at the 10 picosecond level, normal statistics applied to the 1800 data entries predict time resolution at the 2.3×10^{-13} sec level. Because of the excellent short term stability of the maser **each pass alone** would allow a frequency comparison at a level of 2×10^{-15} . As time goes on, and data are accumulated over many days, considerably higher comparison precision could be obtained.

Apart from using the HMC laser time transfer system for use in evaluating the maser's frequency stability it is obvious that, by involving other laser sites, the HMC experiment could demonstrate the capability of intercontinental time transfer at the sub-50 picosecond level¹⁶. Such time transfer accuracy would provide new resources for science, technology and high data rate communications systems.

Measurements of the binary pulsar^{17,18} have challenged the accuracy and long term stability of the best accessible clocks. These measurements would be greatly improved with accurate time transfer to the world's best clocks. From letters of endorsement for HMC that we have received from NIST and the U.S. Naval Observatory, we know that the claimed accuracy of newly developed cesium clocks in various nation's standards labs is now at levels far better than the present ability to compare them. These letters are included in Appendix 1.

4 Status HMC Maser Hardware Design, Construction and Testing

This section describes the status of the atomic hydrogen maser system designed and built at SAO for the H Maser Clock (HMC) space-borne test aboard the Russian Space Station, Mir. A block diagram of the major components of the HMC experiment system is shown in the lower part of Figure 4.

Table 1 is a summary of the mass of the HMC components

4.1 Design of the HMC Maser oscillator Physics Package

The heart of the maser system is the hydrogen maser oscillator. A cross section view of the oscillator is given in Figure 6 outlining the Operating Components and the Controlled Components.

The design of the maser has significant differences from the 1976 version. These differences include:

1. Better thermal control using multiple-layer reflective insulation outgassed into the vacuum of space.
2. Capability of continuous operation for four years or longer by incorporation of hydrogen scavenging systems with greater capacity, and all-metal seals to minimize long term vacuum contamination.
3. Conductive cooling, in place of the circulating gas loop, previously used for cooling the maser's atomic hydrogen dissociator.

4. Better magnetic shielding. Low earth orbiting payloads are subject to the earth's magnetic field at a level of about 0.5 Gauss. These fields vary in direction as the payload orbits the earth. To cope with these fields, the HMC has passive magnetic shielding and active compensation. Magnetic tests on the space hardware indicate that the maximum fractional frequency shift owing to the expected field variations is well below 1 part in 10^{15} .

The physics package was designed to cope with the dynamic loads associated with shuttle launch, a sample of the ANSYS structural analysis is shown in Figure 7. Figure 8 shows the critical "Forward structure" shown in Figure 7 installed for vibration tested at Qual levels to assure its survival after launch. A separate series of dynamics tests confirmed the resonance frequencies and dynamic oscillation "Qs". The space maser's mechanical design satisfies the dynamic requirements for shock, vibration and acoustic loads of the Atlas II system, so that future masers of this type could be flown on expendable launch vehicles as well as on the Space Shuttle.

STATUS: The maser began oscillating in the Laboratory environment in May of 1996 and continues to operate with excellent results. The Physics Package was installed in a vacuum tank in August 1996. Thermal testing and adjustment of control parameters were performed in December 1996 and January 1997. Operation of the maser continues to this date (June 3, 1997) .

Figure 9 shows the frequency stability measured using SAO VLG maser P-13. (The SAO Lab reference maser.) The HMC Contract End Item Specification is also shown.

4.2 Spacecraft interface

The mechanical interface to the Mir space station has been designed. Figure 10 shows the mechanical structure housing the HMC as it was to be installed on the Mir Docking Module. Procurement of materials for its construction was begun, and some of its parts were fabricated. The neutral buoyancy model was built and shipped to JSC for tank testing and was well accepted. Figure 11 is a photograph of the neutral buoyancy model.

4.3 Software:

The instrument control firmware is complete and has been thoroughly tested. Flight software for HMC's Dedicated Experimental Processor (DEP) has been written and tested for Mir mission requirements.

4.4 Electronics

In the following sections, the status of all HMC sub-systems and assemblies will be discussed, along with additional descriptive material where necessary to help define the performance objectives of the HMC project.

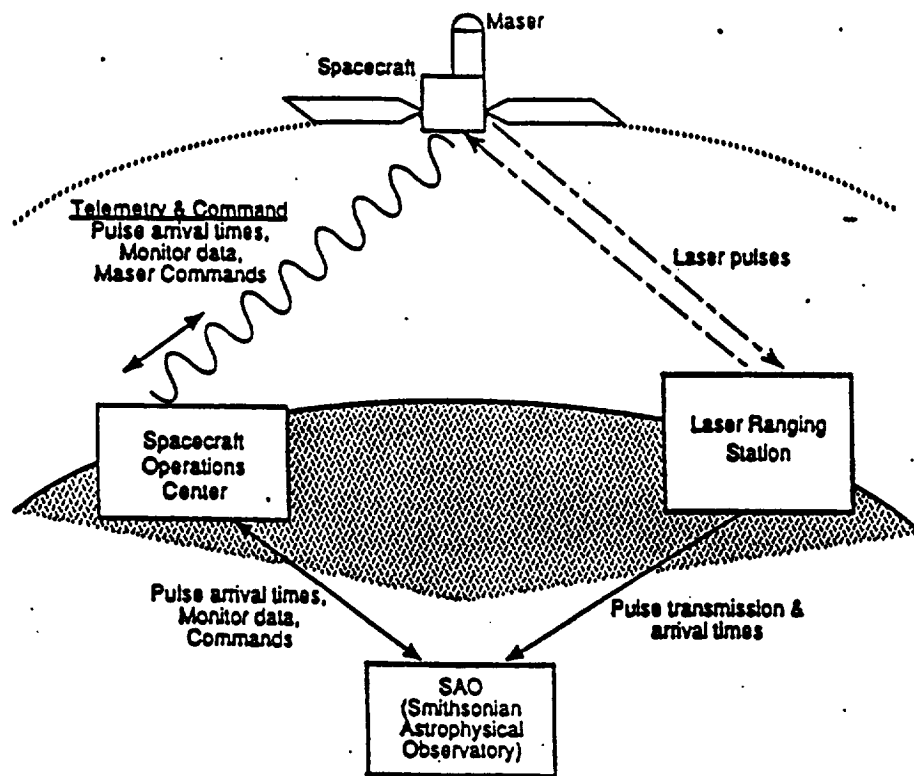


Figure 1

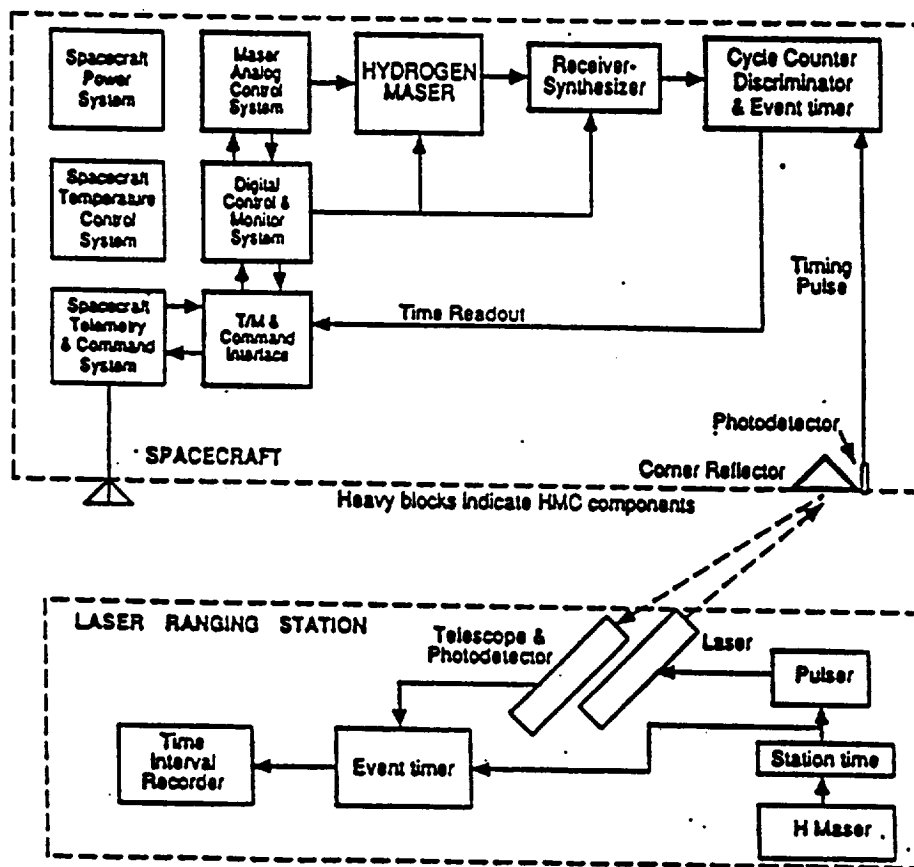
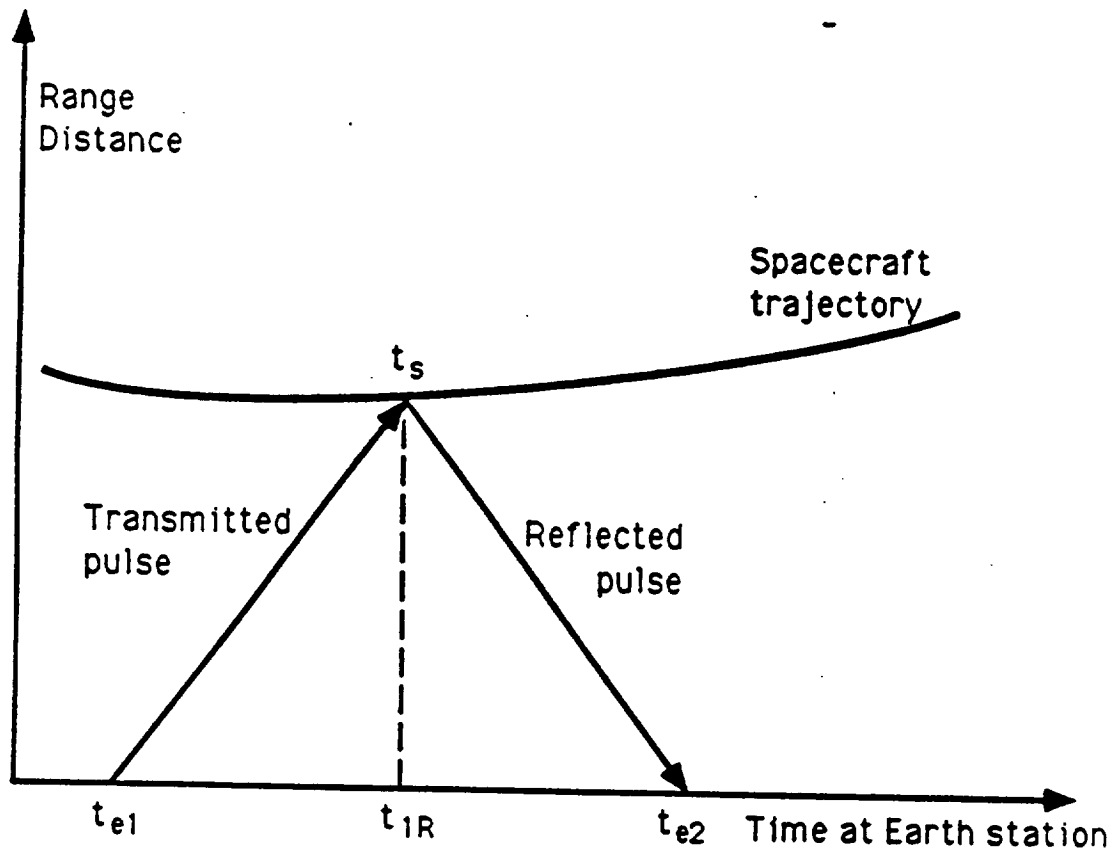


Figure 4

An overview of the HMC experiment time transfer system and a block diagram of its major components



t_{e1} = time of laser pulse transmission as measured by earth station clock

t_s = time of detection at spacecraft as measured by spacecraft clock

t_{1R} = time of pulse arrival at spacecraft in terms of earth clock
 $= (t_{e2} - t_{e1}) / 2$

$\Delta t_{se} = t_s - t_{1R}$ is the difference between the pulse arrival times measured by the space and earth clocks, corrected for propagation delay:

$$\Delta t_{se} = (t_s - t_{1R}) = t_s - \left(\frac{t_{e1} - t_{e2}}{2} \right) - t_{e1} = t_s - \left(\frac{t_{e1} + t_{e2}}{2} \right)$$

Figure 5
 Schematic light-time diagram for the time comparison process

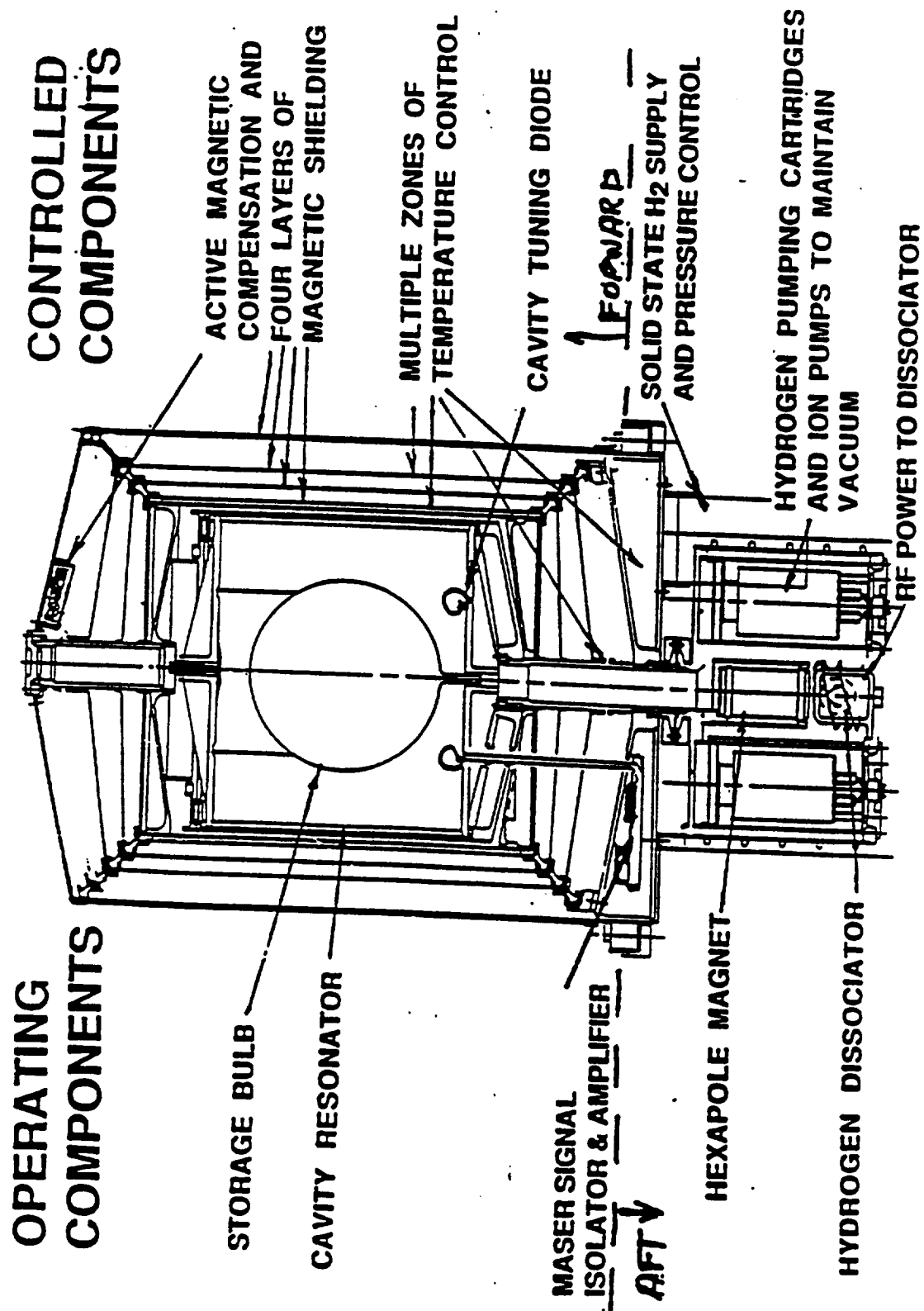


Figure 6
Cross section of the Physics Package showing Operating Components and Controlled Components.

MASS SUMMARY

MASS TABLE (Kg)

ITEM	LAST (27 Mar 96)	CURRENT (01 Jun 96)
<u>PHYSICS UNIT:</u>		
Forward	51.3	51.3
Aftvac	<u>19.4</u>	<u>19.4</u>
TOTALS	70.7	70.7 *

THERMAL RADIATOR AND STRUCTURE:

Thermal components	8.8	8.8
MIR RS equipment	27.7	27.7
EVA handles	5.8	5.8
AFT cove	2.7	2.7
Primary structure	18.4	18.7
Misc.	1.3	1.3
Ref/Evntmr-Mtg & Cover	<u>1.7</u>	<u>1.7</u>
TOTALS	66.7	66.7

ELECTRONICS:

Receiver	2.3	2.6*
DEP	3.8	3.8*
ECU	12.0	14.4
Ref/Evntmr	5.0	5.0
Cabling & Connectors	3.5	3.5
Battery unit	12.7	12.7
Power control unit	3.6	3.6
GPS	3.4	1.9
Electronics Plate	<u>8.9</u>	<u>8.9</u>
TOTALS	55.2	56.4

TOTAL MASS MIR EXPERIMENT 193.3 Kg 193.8 Kg

TOTAL MASS ALLOWED ON MIR \leq 200 Kg

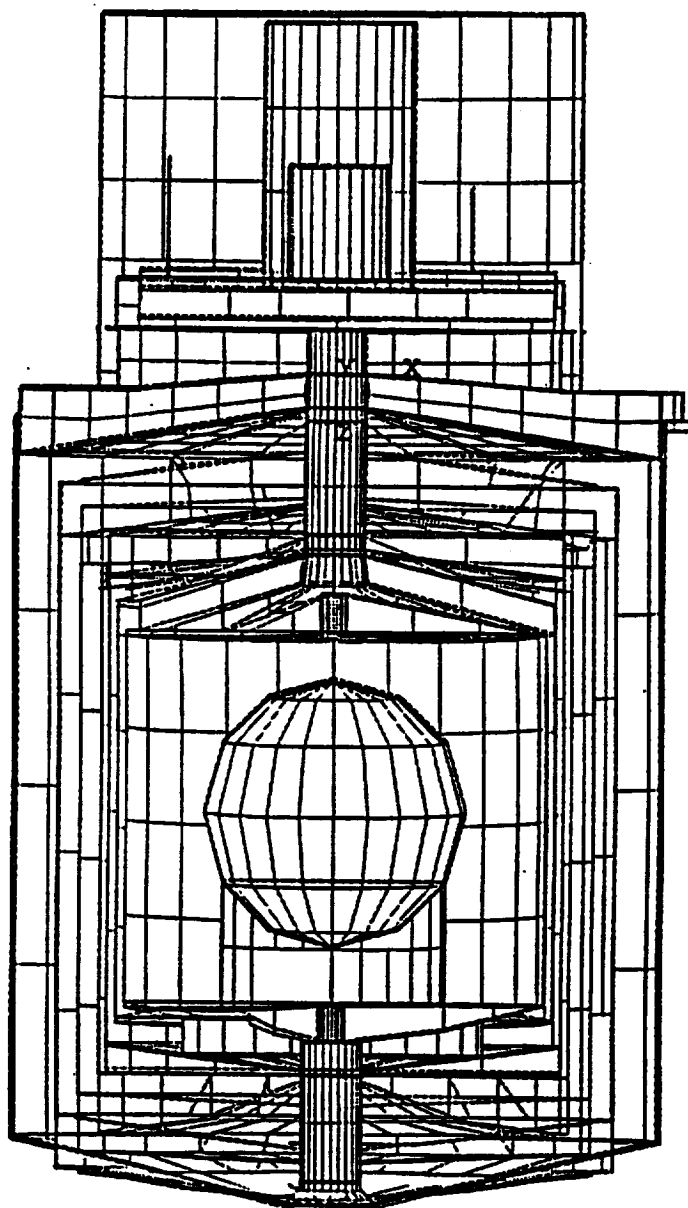
TOTAL EXPERIMENT CONTINGENCY 7.4 Kg (3.7%)

* This mass is actual weight measurement.

TABLE 1

SAO
HMC





ANSYS 5.0 A
OCT 4 1995
10:40:51
PLOT NO. 1
DISPLACEMENT
STEP=1
SUB =1
FREQ=44.808
RSYS=0
DMX =0.062156
SEPC=95.822

DSCA=27.69
YV =1
DIST=17.256
XF =0.431496
YF =-4.311
ZF =6.23

4IR/MSR CDR Update; w/ cor. dissoc. wt. & thl shld t=.062

MODE SHAPE, $f_1 = 44.4 \text{ Hz}$
FOR "PHYSICS PORTION" OF HMC ASSEMBLY

Figure 7
Sample of the ANSYS structural analysis of the HMC Physics Package



Figure 8
"Forward structure" on shaker
for vibration tests at Qual levels

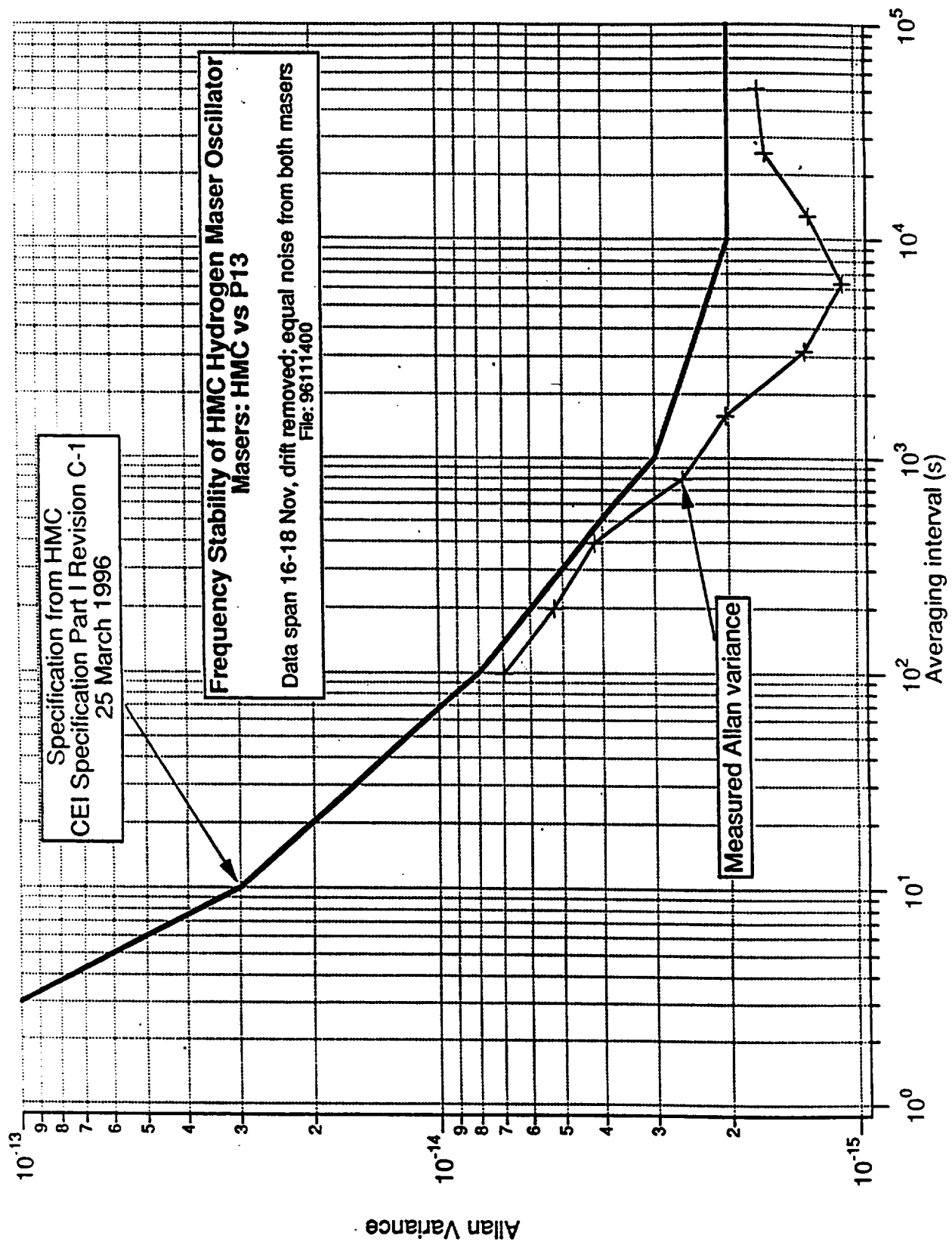


Figure 9
HMC Maser frequency stability

HMC INSTALLED ON DM

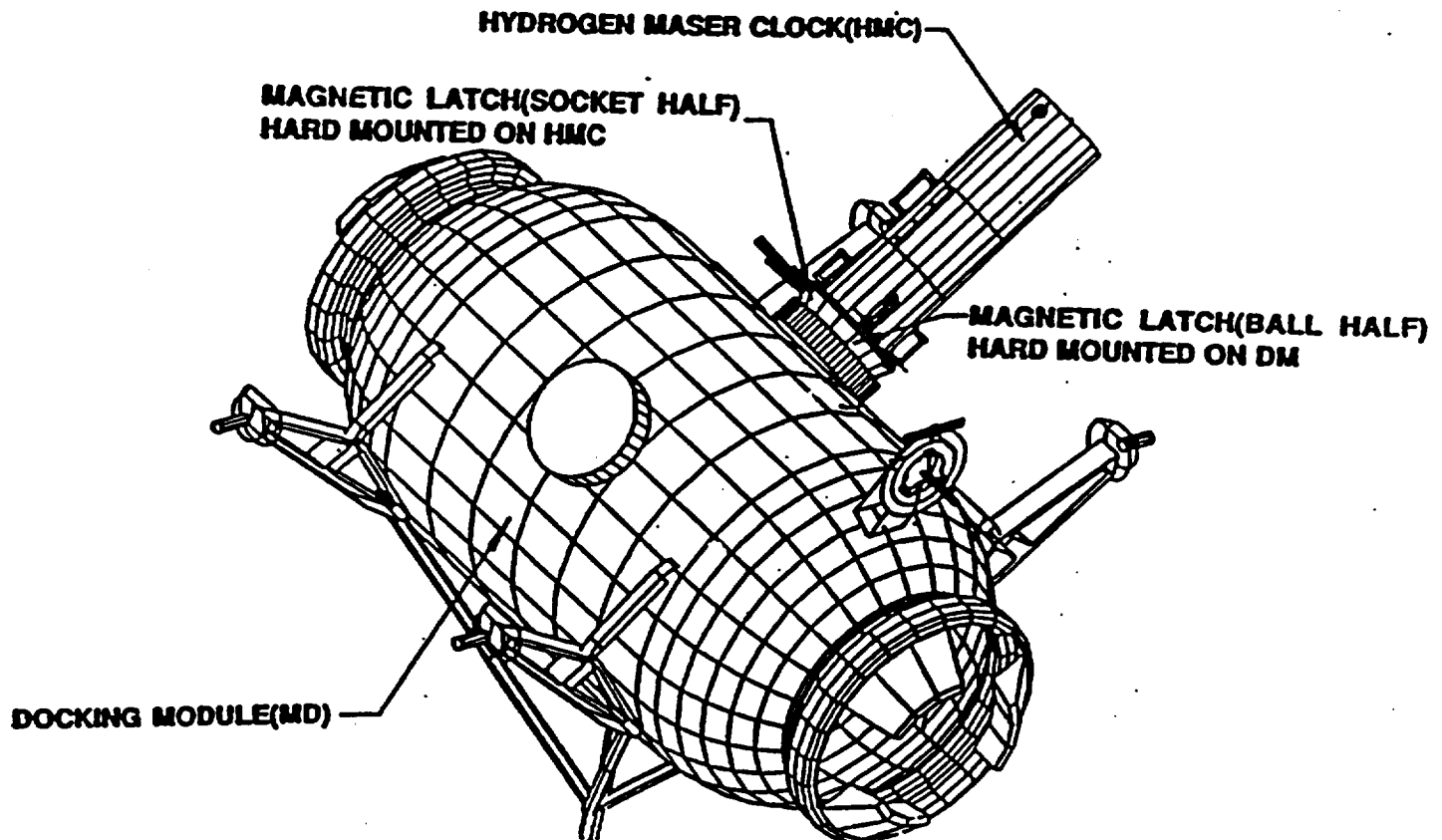


Figure 10
Mechanical structure housing the HMC for installation on the Mir Docking Module



Figure 11
HMC neutral buoyancy model

To clarify the status of the various components and systems, mention will occasionally be made of work required to adapt the existing hardware for use on the Atomic Clock Ensemble in Space (ACES), a proposed joint NASA-ESA Mission involving testing of atomic clocks on the Space Station Express Pallet.

The HMC's electronics for Mir are complete and will remain largely unchanged for the ACES mission. All electronics have been designed and built to NASA flight standards, and continue under test with the maser at the present time. The circuit boards and housings will be rebuilt to accommodate the Express Pallet configuration and thermal requirements. The tested circuit designs and layouts will not be changed.

The major HMC electronic assemblies are:

- 1) Electronics Control Unit (ECU)
- 2) R.F. receiver
- 3) Preamp/isolator
- 4) Diode bias supply
- 5) R.F. source
- 6) Dedicated Experiment Processor (DEP)

A block diagram of the complete HMC electronics system is shown in Figure 12. The supporting electronics can be divided into two categories, Control and Monitoring Electronics and Supporting Electronics

4.4.1 Control and Monitoring Electronics

The frequency stability of the maser is affected primarily by systematic variations in the maser's internal environment, including temperature, magnetic field and hydrogen beam flux. To achieve the desired frequency stability, all of these parameters must be carefully controlled.

1)- The physics unit control and monitoring subsystem directly influences the operation of the Maser physics package temperature, magnetic field controls, cavity tuning diode bias supply, atomic hydrogen dissociator, and hydrogen pressure regulator.

2)- The data and command subsystem coordinates the operation of the Maser subsystems with the spacecraft command and data handling system control computer.

The Control Electronics are housed in the Electronics Control Unit (ECU) assembly.

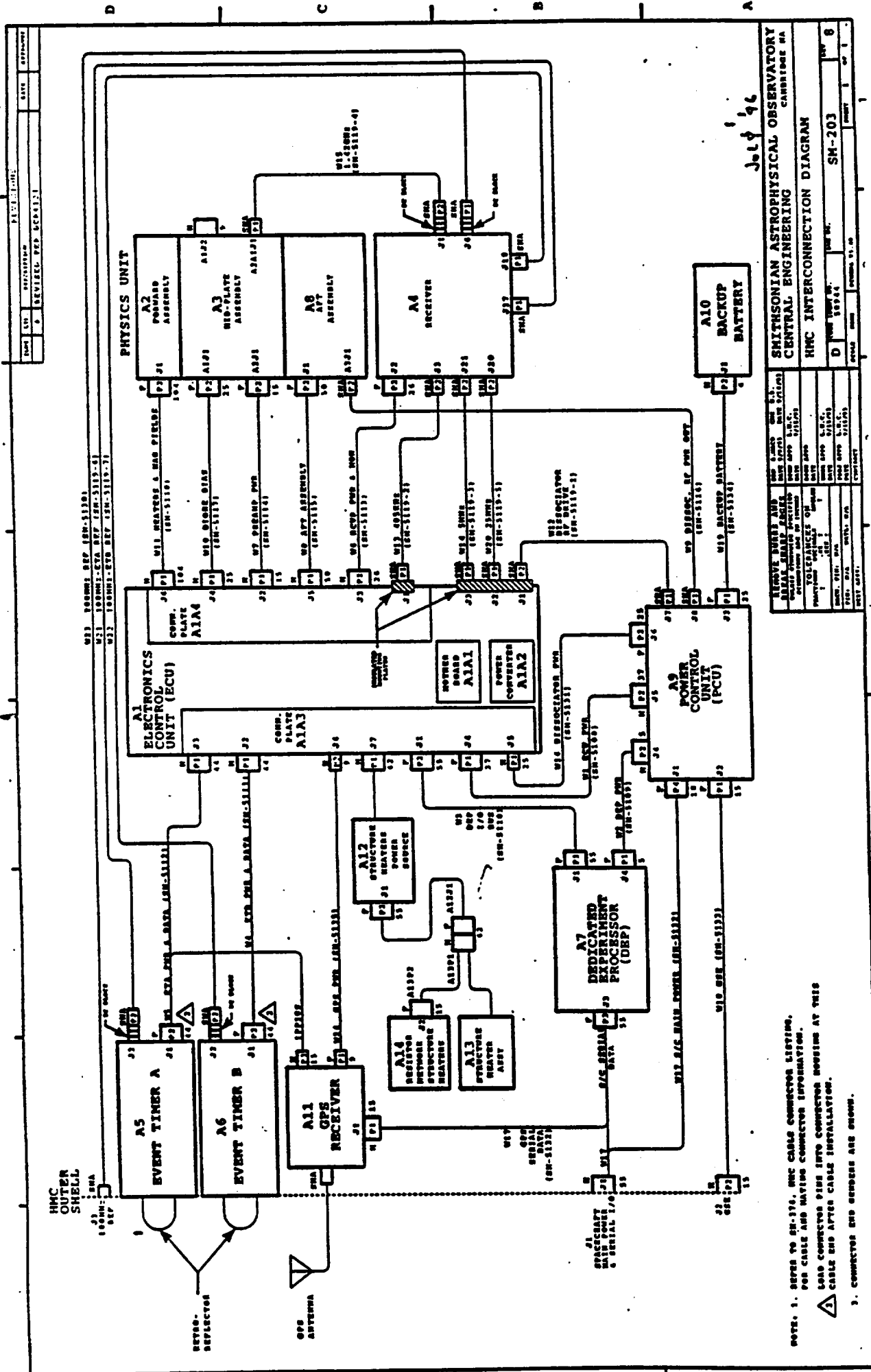


Figure 12
Block diagram of the complete HMC electronics system

The ECU contains printed wiring boards spaced on 2.2 cm centers. In addition, there is a motherboard carrying digital signals and power to all the cards.

The ECU boards are: Four Thermal Controllers, one Magnetic Field Control, one Hydrogen Pressure Controller, one to Control the R.F. hydrogen dissociator and one for miscellaneous functions, (the multifunction card that operates the tuning diode bias control, miscellaneous data acquisition, the system clock and the system reset).

4.4.1.1 Thermal Control:

The stability of the maser output frequency depends significantly upon the thermal stability of its microwave cavity. In order for the maser to perform to its rated stability, the cavity must be stabilized to about 100 micro degrees Celsius¹⁹. To achieve this level of temperature control, the maser structure is divided into three concentric isothermal control regions. Each region establishes the external environment for the next inner region. Thermal gradients are controlled by subdividing each isothermal region into multiple independently controlled zones. All regions and zones are cylindrically symmetric.

The HMC has 17 thermal control zones, as listed below.

Temperature Control Zones:

Three Ultra-high stability zones (0.0001 degree Celsius) 1) Tank Cylinder 2) Tank Forward 3) Tank End

Four High stability zones (0.001 degree Celsius) 1) Mid Plate 2) Oven Cylinder 3) Oven Forward 4) Oven Aft

Four Medium stability zones (0.01 degree Celsius) 1) Neck Aft 2) Neck Forward 3) Pirani Enclosure 4) Preamp Isolator

Six Low stability zones (0.1 degree Celsius) 1) Diode Bias, 2) ECU Enclosure, 3) Structural Heater A, 4) Structural Heater B, 5) Structural Heater C, 6) Structural Heater D.

Two additional temperature control zones (for the palladium valve and the H₂ reservoir) are controlled from the Hydrogen Pressure Control board and are discussed in another section.

The four Temperature Control Boards plug into the ECU. Each board controls five independent thermal zones, all under the control of a single time-shared 68HC11A1 micro controller (MCU) on the board. The temperature of each zone is controlled by sensing the temperature with a thermistor and controlling power to the zone heater.

The temperature controller circuits all use high stability glass bead thermistors as temperature sensing elements. The thermistor in each thermal zone is connected in a resistance bridge, the output of which is amplified and brought to one of the analog inputs of the micro controller. The internal 8 bit A/D converter in the micro controller digitizes this signal. A firmware program calculates the appropriate heater power. The firmware converts the result to a pulse width modulated (PWM) switching wave form. This PWM signal drives the zone heater, adjusting the temperature to balance the bridge. Supply voltage to each of the switching power amplifiers is enabled by a magnetic latching relay.

Analog housekeeping signals include heater current, amplified bridge output (i.e. servo error), and zone temperature as read by the monitor thermistor are monitored for all five channels of each temperature control board.

STATUS: The functioning of these controllers has been verified. The thermal control system has been tested with excellent results and is currently operating the maser.

4.3.1.2 Magnetic Field Control:

A requirement for proper maser operation is a stable and uniform longitudinal magnetic field within the hydrogen interaction bulb with a magnitude on the order of 0.5 MilliGauss. Four nested cylindrical magnetic shields isolate the maser from external fields. Three magnetic field control solenoids mounted on the outside of the vacuum tank are used to maintain this field. Currents in the solenoids must be controlled with a stability of 100 PPM. A fourth field control solenoid is used in a feedback loop to actively compensate for variations in the external magnetic field. A single axis flux gate magnetometer serves as the sensing element for this active control system. The total shielding factor, $\Delta B_{\text{external}}/\Delta B_{\text{internal}}$, of the combined passive and active shielding system is 2×10^6 .

Steady-state magnetic field control.

A temporally constant, spatially uniform magnetic field of constant magnitude must be maintained within the maser physics unit for proper operation of the maser. A three-fold approach is used in the design of the HMA system to achieve this field.

As described earlier, a series of nested passive magnetic shields that surround the maser's resonant cavity and hydrogen storage bulb alternate the external field, and isolate the maser from variations in the local magnetic field.

Further to isolate the maser from variations in the external field, there is an active magnetic field compensation circuit consisting of a magnetic field sensor located inside the physics unit, and a magnetic compensation coil wound around one of the passive shields. The output of the sensor serves as a servo loop error signal when the compensation coil is enabled. When the coil is off it provides a measure of the local magnetic field.

Finally, the constant, uniform magnetic field in the hydrogen storage bulb is created by supplying carefully controlled, highly stable steady-state currents to a three-section solenoid surrounding the maser cavity.

STATUS: These systems have been tested and their functioning has been verified.

The sweeper performs a diagnostic test to determine the magnetic field intensity in the storage bulb. The "Zeeman resonance frequency" is the frequency at which transitions are made between the $F=1$, $M_F = 1, 0$ and -1 hyperfine magnetic sublevels shown in Figure 1. During a sweep of these frequencies these induced transitions reduce the output power of the maser, as indicated by the receiver IF level. This frequency is related to the magnitude of the magnetic field within the bulb.

The entire Zeeman sweep sequence is carried out by a pre-programmed sequence of commands stored in the DEP.

The initial Zeeman sweep is done at a relatively high amplitude, giving a broad indication of resonance. Accuracy of the measurement can then be improved by decreasing the amplitude of the a-c field for each subsequent sweep, since the sharpness of the resonance is greater at lower amplitudes. The amplitude and frequency of the a-c field are both programmable by the DEP.

4.3.1.3 Hydrogen Flow Control:

A steady flow of Hydrogen is needed to maintain maser oscillation. Hydrogen gas is supplied from a heated canister containing Lithium Aluminum hydride (LiAlH_4). Hydrogen flow to the dissociator bulb is regulated by a thermally controlled palladium valve.

Hydrogen gas for the dissociator is supplied by a two-stage control system. In the first stage, a stainless steel canister containing granular lithium aluminum hydride (LiAlH_4) produces hydrogen gas at a controlled pressure of approximately 50 psia. From the source canister, the hydrogen gas flows to a heated palladium-silver flow control diaphragm that further regulates the pressure down to a level of about 0.01 Torr. Pressure on the low side of the palladium valve is sensed by two redundant Pirani thermistors. From the palladium valve, the hydrogen flows to the dissociator bulb, where it is dissociated into individual atoms by electron bombardment by a glow discharge sustained by an R.F. field. On the H2 Pressure Controller board, a latching relay, controlled by the DEP, selects one Pirani gauge or the other to be the sensor input to the low-pressure control loop. The outputs from both gauges are independently monitored by analog housekeeping.

In the same way as the temperature controller boards, the state of the heater power relays is reported to the MCU so that the PWM control algorithm can be disabled in firmware if the power to the heater has been switched off. The H2 Pressure Controller board also contains latching relays that switch 28 volt power to the two ion pumps in the physics unit. The states of these relays are managed by the DEP.

STATUS: This system's performance has been verified and tested with excellent results.

4.3.1.4 Cavity Resonator Tuning Assembly

The resonant frequency of the maser cavity is adjusted for optimum maser stability by the tuning diode voltage controller. This circuit responds to commands from the ground to adjust the DC bias voltage on a varactor tuning diode within the maser cavity.

This assembly is mounted in the physics package and is temperature stabilized.

STATUS This system has been tested with excellent results.

4.3.1.5 Data and command sub-system

Dedicated Experiment Processor (DEP) assembly

The microprocessor system allows flexibility in interfacing with the command and monitoring systems in a wide range of vehicles. This system also allows us to pre-program a number of processes related to the operation of the physics package and the receiver-synthesizer. Its use makes the maser independent of spacecraft software; only an interface card is required to match the spacecraft's data handling or telemetry system. The Dedicated Experiment Processor (DEP) is a 80186-based microcomputer housed in a separate assembly, 17 by 27 by 14 cm and weighing 6 kg. The assembly is a five-slot card rack with a printed wiring back plane, containing four plug-in cards and a DC/DC converter for supplying power to the computer. Power dissipated is 8 watts.

STATUS This system has been tested with excellent results.

4.3.1.6 Maser signal processing and R.F. receiver assembly

This is a module whose function is to produce an output signal at useful power levels and at standard frequencies, such as 100 MHz, 50 MHz, etc., that are related closely to the definition of the international time scales. The output frequency is adjustable in steps of a few parts in 10^{17} so that frequency control and time synchronization with other systems such as the Pharaos can be achieved.

The R.F. receiver phaselocks a 100 MHz voltage-controlled crystal oscillator to the maser's low-level 1.42 GHz output signal, providing high-level buffered signals at standard frequencies (1200 MHz, 100 MHz, 25 MHz and 5 MHz). The receiver consists of four printed wiring boards mounted inside an aluminum housing. The receiver dissipates less than 10 watts.

The maser R.F. receiver is a low noise, extremely phase stable, triple heterodyne phase lock loop. Its design has been proved by many years of operation in SAO ground masers. The reference signal for the phase detector is the output of the digital frequency synthesizer. The reference signal for the synthesizer in turn is derived from the receiver's 100 MHz phase locked crystal oscillator, so that the entire system is phase coherent with the maser output. The 100 MHz signal is buffered and brought out as an external reference signal.

The DC output of the phase detector is amplified and integrated and used to tune the 100 MHz voltage controlled crystal oscillator (VCXO). An auxiliary in-phase mixer in the integrator module measures the maser signal level. This signal, termed the "IF level," is used for monitoring the maser's R.F. power output.

The Isolator/Preamplifier assembly, which is in the Physics Package and conveys the maser signal to the receiver, consists of a 60 dB passive ferrite isolator and a 24 dB gain 1.42 GHz amplifier module. The isolator reduces the effects of variations in external circuit impedance on the cavity resonance frequency, while the preamplifier provides low-noise first stage amplification of the maser's -100 dBm output signal. Because variations of isolator impedance transmitted via the line carrying the signal from the maser resonator can cause maser frequency perturbations, and can vary with temperature, the preamp/isolator box is temperature controlled. The preamplifier dissipates 1/4 watt. This assembly is physically located within the physics package.

The Digital Frequency Synthesizer board is a single printed wiring board housed inside the R.F. Source Unit. The function of this board is to provide a programmable reference frequency in the vicinity of 405 KHz to the phase-locked loop in the receiver.

The clock reference frequency used in the HMC synthesizer is 5 MHz, giving a full output range of 0 to 2.5 MHz, settable in increments of 1.77×10^{-8} Hz. In practice, the frequency range is always kept in the range 405,740 Hz to 405,760 Hz.

STATUS The receiver system has been tested with excellent results, and is in storage. Present H-maser operations are being done with a laboratory receiver-synthesizer system. The isolator/preamp system is in operation in the flight physics package and has been tested with excellent results.

4.3.1.7 Dissociator oscillator assembly

The R.F. source assembly produces a 60-70 MHz signal at 4-5 watts to operate the maser's hydrogen dissociator, which converts molecular H₂ into atomic hydrogen. It consists of two printed wiring boards, a power amplifier module, a DC/DC converter and two directional couplers for measuring the forward and reflected output power to the dissociator. It produces up to 8 watts of R.F. power at 65 MHz.

The R.F. Source control board is a single plug-in printed wiring board housed inside the ECU. This board provides a serial interface to the Dissociator Exciter board and

the Frequency Synthesizer board (both located in the R.F. Source Unit) and it controls the output power of the Dissociator Power Amplifier.

The Dissociator Exciter board is a single printed wiring board housed inside the R.F. Source Unit. This board performs two functions in controlling the dissociator:

(1) It generates a signal with programmable frequency in the range of 60-70 MHz to the input of the dissociator power amplifier.

(2) It supplies signals to enable the dissociator power supply and to control the dissociator overload protection system.

STATUS The flight amplifier system has been tested with excellent results. The flight hardware power amplifier is in storage; the maser is currently being operated from an external lab R.F. power supply.

5 Conclusions

5.1 Summary of test results.

Tests have been conducted show that the HMC system has satisfied the requirements for the Mir mission.

• Frequency Stability Measurements

The frequency stability of the maser has exceeded the HMC contractual design requirements.

• Mechanical Tests

The mechanical design of the critical forward assembly of the physics package housing the cavity resonator has been verified by dynamic testing at Qualification Levels. The mechanical resonance frequencies of the resonator structure and the Q of their mechanical resonances has confirmed the computer analysis.

• Thermal Tests

The thermal control system will cope with the extremes of temperature expected within the external housing. The expected sub milliKelvin performance at the cavity resonator was confirmed by measurement.

• Magnetic Tests

Simulations of the variation expected from external magnetic fields encountered from operation in a low earth orbit show that changes in the maser's internal magnetic fields have been reduced to levels well below our ability to measure them in terms of

maser output frequency shifts. These measurements were made using the maser as a super sensitive magnetometer.

- Vacuum Pumping and Hydrogen Scavenging

The combined sorption and ion pump system used for hydrogen scavenging and vacuum maintenance has operated continuously for eighteen months in the engineering model of the physics package and reactivation of the cartridges showed no deterioration. The same system has operated continuously in the flight maser for fourteen months and shows no sign of any problem. Pressure inside the maser during operation is well below 10^{-6} Torr.

- Hydrogen Dissociator

Extensive tests of the RF dissociator which, in the HMC maser is located entirely within the vacuum system and cooled by thermal conduction, show no change in dissociator efficiency over more than two years of operation. These tests were conducted on both the engineering model and on the flight model.

- Receiver synthesizer

This design has been used in all the SAO VLG-11 series ground masers and, in the re configured flight hardware, has shown no problems.

- Dedicated Experiment Processor (DEP)

Most of the software for startup, maser diagnostics and maser operation on Mir has been written and tested. This software will require modification for use on other spacecraft. The command and monitoring systems are completely operational and have been in continuous use for over a year. During tests, the data (formatted from the DEP) have been collected on floppy discs.

- Mechanical Structure for Containing HMC and attaching it to Mir.

The structure was designed and mechanically tested by computer simulation. Construction was halted. The Neutral buoyancy model was designed, built, shipped to the Johnson Space Center, successfully tested and approved for Extra Vehicular Activity operations.

With internal support from SAO, we expect to continue operating the HMC and collecting frequency stability data until Dec 1997.

5.2 Major Improvements to H-Maser Technology in HMC

- Event timer with a 10 picosecond time resolution. This was developed for HMC by the Los Alamos National Laboratories
- Sub milli-Kelvin thermal design.
- Magnetic compensation to cope with 0.5 Gauss external field variations

- Mechanical design for space launch
- Microprocessor controlled automated operations, command and monitoring.

5.3 Present Situation and Possible Future application of the HMC Flight Hardware

Owing to serious budgetary constraints, the present state of research and development of frequency standards in the USA is in a very precarious state*. Descoping of the SAO/NASA HMC project is but one manifestation of this situation. However, as of June 1997, the key people who were employed on HMC at the SAO maser lab are still employed at SAO, and the Maser Lab is intact. As has been reported here, the design of the HMC flight equipment is in good shape and well tested. Also, the flight hardware is in a state of good preservation at SAO.

We are now actively seeking new NASA flight opportunities on the International Space Station to continue the work of evaluating the operation of the HMC space flight hardware, conducting tests of relativistic gravity and demonstrating global high precision time synchronization.

*Alvenot
SAO Cambridge Massachusetts
June 13, '97*

* See Appendix 1

"Summary Trip Report" March 28, 1997

Donald B. Sullivan, Chief, NIST Time and Frequency Division, Boulder CO

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-
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6 Appendices

Appendix 1 Letters and Trip Report

- "Summary Trip Report" March 28, 1997
Donald B. Sullivan, Chief, NIST Time and Frequency Division, Boulder CO
- Prof. J.H. Taylor, Princeton University to Mr. S. Davis NASA MSFC
- Dr. W.J. Klepczynski U.S. Naval Observatory to R.F.C. Vessot SAO
- Dr. D.D. McCarthy U.S. Naval Observatory to Mr. S. Venneri NASA HQ
- Dr. D. B. Sullivan NIST to Mr. S. Davis NASA MSFC
- Prof. V Tatarenkov VNIIFTRI (Russia) to R.F.C. Vessot SAO



**UNITED STATES DEPARTMENT OF COMMERCE
National Institute of Standards and Technology**

325 Broadway
Boulder, Colorado 80303-3328

Reply to the attention of:

March 28, 1997

SUMMARY FOREIGN TRIP REPORT

From: Donald B. Sullivan, Chief
NIST Time and Frequency Division

Location visited: Neuchâtel, Switzerland — March 4-8, 1997

Purpose of trip: To attend the European Frequency and Time Forum (EFTF) and present a short paper at a special session of the conference.

Accompanied by: No one

Trip Summary: For the last several years I have had a growing concern that the United States is falling behind Europe in research and development on high performance clocks and oscillators. The work presented at this conference convinced me that leadership in this field has now shifted to Europe. This is especially distressing because most of the concepts in this field were developed in the U.S., and we have led their application to critical technologies such as satellite navigation (GPS) and high-data-rate telecommunications. If the level and quality of R&D is an accurate indicator of success in the future, the U.S. is likely to find itself well behind Europe in this field during the next decade.

While at the conference, I discussed this impression with two other U.S. attendees, Bob Vessot of the Harvard-Smithsonian Astrophysical Observatory and Bill Riley of EG&G Corporation. Both of these (senior people in the field) agreed with this assessment. The work being done in Europe seems well supported, of high quality, and spans the spectrum from very basic research to applied developments that should get into the marketplace in the near term. The U.S. still does some high quality work in the field, but there are very notable gaps where the U.S. is doing virtually nothing. The direct market for products in this technology is not large, so there is very little investment being made in it by U.S. industry. Yet this technology is absolutely critical to the success of a wide range of military, aerospace and telecommunications systems. Action should be taken to assure a strong U.S. position in the field.

For 50 years, NIST has played a key role in this measurement technology. Considering the deteriorating U.S. position in the field, it is more important than ever that NIST maintain strength in its current program.

Princeton University

DEPARTMENT OF PHYSICS: JOSEPH HENRY LABORATORIES
JADWIN HALL
POST OFFICE BOX 708
PRINCETON, NEW JERSEY 08544

June 10, 1996

Mr. Stephan Davis
Mail Code FA64
George C. Marshall Space Flight Center
Huntsville, AL 35812

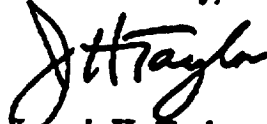
Dear Mr. Davis:

I am writing to convey my strongly held opinion that your program to put a Hydrogen Maser Clock (HMC) on board the Russian space station Mir is an important and unique one, and should be completed.

There are many obvious uses of the HMC in connection with the time-keeping and time-transfer activities of the United States Naval Observatory and the National Institute of Standards and Technology. What may not be so evident is that other scientific programs, including my own work on very high precision timing observations of pulsars, will benefit from more stable time standards than are now available. In effect, these astrophysical studies of pulsars compare "pulsar time" with atomic time. Because the stability of some pulsars is extraordinarily high, the experiments require the best possible reference time scale to achieve full accuracy.

The HMC experiment can help significantly to provide this important ability. The results could be of great benefit to a number of studies in cosmology, fundamental astrometry, and gravitation physics.

Yours sincerely,



Joseph H. Taylor
James S. McDonnell Distinguished
University Professor of Physics

8 April 1996

Dr. Robert Vessot
Smithsonian Astrophysical Observatory
Hydrogen Maser Laboratory
Cambridge, MA 02138

Dear Dr. Vessot:

It was with great interest that I read about the proposed experiment to place an Hydrogen Maser Clock (HMC) on board the Russian Space Station, MIR, via transport by the NASA Space Shuttle.

This experiment has great application in the field of Precise Time and Time Interval (Frequency). There are two areas where it could make a significant contribution. One is in the area of Time Transfer Calibration. By using a laser event timer on-board the spacecraft along with a retro-reflector, it would be possible to record the time of reception of laser pulses emanating from ground stations, such as NASA Goddard Space Flight Center, and allow the ground stations to record the round trip time to the spacecraft. This would eventually allow time transfer at about the 100 ps. level over a wide area and, thus, allow for the calibration of other ground and space based timing systems. This would be similar to the previously proposed LASSO Experiment but would have the added advantage of having a HMC in space.

The other area where it could make a significant contribution would be in the evaluation of the newest frequency standards being developed around the world. These devices look like they will have an accuracy and stability better than a part in ten to the fifteenth. It would allow for the comparisons of these devices over much shorter intervals of time. This would speed up their development and save considerable sums of money in the R&D area.

While it would be impossible to contribute to the experiment monetarily, you can be assured that we will follow its progress with the hope of participating in some modest fashion. If GSFC were one of the participating stations, it might be possible to help them with their timing requirements for this experiment.

Sincerely yours,



William J. Klepczynski
Department Head
Time Service Department
U. S. Naval Observatory
Washington, DC 20392-5420



U.S. NAVAL OBSERVATORY

DIRECTORATE OF TIME



Dr. Samuel Venneri
Chief Technologist
National Aeronautics and Space Administration
Washington, DC

Dear Dr. Venneri:

I am writing to express my interest in the Hydrogen Maser Clock Experiment. It is a worthwhile and useful experiment in which the U. S. Naval Observatory would hope to participate by providing a link from the Master Clock to the Goddard Space Flight Center and by participating in the data analysis. I hope that you will give this project your earnest consideration.

Sincerely,

Dennis D. McCarthy
Director, Directorate of Time



UNITED STATES DEPARTMENT OF COMMERCE
National Institute of Standards and Technology
325 Broadway
Boulder, Colorado 80303-3328

Reply to the attention of:

February 14, 1996

Mr. Stephan Davis
Mail Code FA64
George C. Marshall Space Flight Center
Huntsville, AL 35812

Dear Mr. Davis:

I have followed the NASA plans to place a hydrogen maser clock (HMC) aboard the Russian Space Station Mir in 1997. This is a highly interesting experiment from my viewpoint, because it provides the potential for comparing widely separated time scales with unprecedented uncertainty. We currently use a special method of common-view GPS time transfer to perform comparisons of time scales and find several limitations. If the HMC experiment could be expanded to allow time observations at other sites with laser ranging stations, it could possibly point the way to a substantial advance in time transfer and shed light on the real performance of presently used systems. Let me elaborate on some of the issues.

First, we must average common-view data over several days to achieve comparisons that are meaningful at the level of performance of these time scales. Our internal measurements suggest that our own time scale drifts at a rate of less than 10^{-16} per day, but it is very difficult, using the common-view method, to check this drift against that of other systems. Second, we are finding it difficult to establish absolute time differences, even at the 10 ns level, between widely separated sites. This is because of poorly understood biases known to exist in GPS. Finally, we have been consulting with the Air Force on GPS for many years, and we would all like to better understand the biases in that system. With the phenomenal performances of the on-board maser and the laser timing links, and with the appropriate partners at other sites (VNIIFTRI in Russia, Grasse in France, Wetzell in Germany, etc.), the HMC experiment could resolve some of these problems. And this would have only minimal effect on the experiments. It is my understanding all that is required is that the timing system aboard Mir log the arrival of additional laser pulses. The ground sites involved could easily perform GPS common-view time transfer during the HMC experiment, so that we would have a good comparison of the two methods.

We are not equipped with the laser ranging equipment, so we could not participate directly, but the outcome of such experiments could have an impact on our programs. I urge you to consider the possibility of expanding the experiment to include such time transfer tests.

Thank you very much for your consideration of the issues I have raised. Please contact me at 303-497-3772 (email: donald.sullivan@nist.gov) if you have any questions.

Sincerely,

Donald B. Sullivan, Chief
Time and Frequency Division



ГОСУДАРСТВЕННОЕ ПРЕДПРИЯТИЕ «ВНИИФТРИ»
ИНСТИТУТ МЕТРОЛОГИИ ВРЕМЕНИ И ПРОСТРАНСТВА
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Телетайп: 205154 МЕРА
Телекс: 411038 KCSV SU

№ _____

На № _____ от _____

March 20, 1996

Fax: (617) 496 - 7690

Dear Prof. Vessot,

In reply to your facsimile message dated 26.02.96 I am pleased to inform you that specialists from our Institute are ready to participate in the "H-Maser Clock" (HMC) experiment.

We have satellite laser ranging system at our disposal with the following characteristics:

- pulse duration - 35 psec
- length of the wave radiation: - 0,532 mkm energy 13 mJ
- 1,006 mkm energy 22 mJ
- resolution of the time interval meter - 60 psec
- diameter of the telescope receiving hole - 500 mm

At the present time the SLR facility is being adjusted. We think that it shall be put into operation by the end of 1996.

Looking forward to receive your proposals on the reglament of measuring data exchange,

Sincerely yours,

V. Tatarenkov

Appendix 2 Recent Papers on HMC project-related Topics

- “High Precision Time Transfer to test an H-Maser on Mir”

R.F.C Vessot, E.M. Mattison, G.U. Nystrom, L.M. Coyle, D.A. Boyd and T.E. Hoffman SAO

- “Precise Temperature Controls for Precision Frequency Standards”

E.M. Mattison, D.A. Boyd, L.M. Coyle and R.F.C Vessot, SAO

- “A 10 picosecond Event Timer for Precise Time Transfer”

E.M. Mattison, D.A. Boyd and R.F.C Vessot SAO
and R.C. Smith, Los Alamos National Laboratory

- “Design of a Hydrogen Maser for Space”

E.M. Mattison and R.F.C Vessot SAO

- “Milli-Celsius- Stability Thermal Control for an Orbiting Frequency Standard”

D.A. Boyd, J.F. Maddox, E.M. Mattison and R.F.C. Vessot SAO

HIGH PRECISION TIME TRANSFER TO TEST AN H-MASER ON MIR

ROBERT F.C. VESSOT, EDWARD M. MATTISON, GEORGE U. NYSTROM, LAURENCE M. COYLE, DAVID BOYD and THOMAS E. HOFFMAN
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PRECISE TEMPERATURE CONTROL FOR PRECISION FREQUENCY STANDARDS

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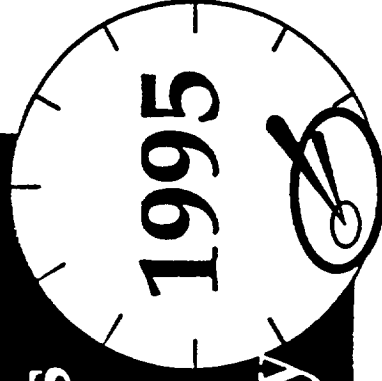
A 10 PS EVENT TIMER FOR PRECISE TIME TRANSFER IN SPACE

EDWARD M. MATTISON, LAURENCE M. COYLE and ROBERT F.C. VESSOT
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Proceedings of the Fifth

**Symposium on
Frequency
Standards
and
Metrology**



Woods Hole, Massachusetts
15-19 October 1995

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HIGH PRECISION TIME TRANSFER TO TEST AN H-MASER ON MIR

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ABSTRACT

A test of a Hydrogen Maser designed for long term operation in space is in preparation for installation on the Russian space station, Mir, in late 1997. The U.S. Space Shuttle will deliver the payload to Mir which will then be transferred from the shuttle cargo bay to the exterior of Mir by U.S. astronauts. Pulsed laser time transfer with a resolution of 10 picoseconds from the primary laser site at the NASA Goddard Space Flight Center at Greenbelt MD will be used to measure the H-Maser's frequency stability. Daily time comparisons made with a precision of better than 86 picoseconds will allow an assessment of the long term stability of the space maser at a level of better than 1 part in 10^{15} . The arrival time of laser pulses will be recorded with a resolution of 10 picoseconds by an event timer on the HMC package and transmitted to earth. The pulses will be reflected back to the earth station and timed with similar resolution to allow removal of the transit time. To provide data for relativistic and gravitational frequency corrections, tracking of Mir with a precision of 1 meter in altitude and 1 mm sec^{-1} will be done with an on board GPS receiver located in the HMC package. We expect other laser sites in addition to the one at GSFC that have access to high precision time to participate in using this opportunity to demonstrate high precision world wide time transfer.

1. Introduction

The design of a space-worthy hydrogen maser capable of four or more years of continuous operation in space has been completed and flight hardware is now being fabricated and assembled. A test of the maser on the Russian Space Station Mir is planned to begin in October 1997. Frequency comparison of the space maser with an earth-based maser will be made with pulsed laser techniques with time resolution of 10 picoseconds. The space borne maser system is operated using an on-board computer that implements a number of automated procedures for controlling the maser and testing its operational parameters. Future space applications of the maser include very long baseline interferometry, improved navigation systems, high precision time transfer and tests of relativistic gravitation.

2. Mission Objectives

The purpose of the Hydrogen Maser Clock (HMC) project is to design, build, and test a space borne atomic hydrogen maser clock system and to evaluate its performance in the space environment. The following tests will be performed:

- (i) Comparison of the maser's frequency relative to international time scales, using laser pulse timing from a satellite laser ranging station equipped with clocks and timing

The diagram illustrates the communication and ranging system between a spacecraft and ground stations. The spacecraft, in orbit, contains a **Spectrometer** and a **Laser**. The **Spacecraft Operations Center (SOC)** on the ground is connected to the **Laser Ranging Station (LRS)**. The SOC sends **Pulse arrival times, Monitor data, Maser Commands** to the LRS. The LRS sends **Pulse transmission & arrival times** to the SOC. The SOC also sends **Pulse arrival times, Monitor data, Commands** to the SOC. The SOC is labeled **Spacecraft Operations Center** and the LRS is labeled **Laser Ranging Station**.

The diagram is divided into two main sections: **SPACECRAFT** and **LASER RANGING STATION**.

SPACECRAFT Section:

- Seismometer System** and **Seismometer Telemetry & Command System** are connected to the **TM & Command Inverter**.
- The **TM & Command Inverter** is connected to the **Signal Command & Control System**.
- The **Signal Command & Control System** is connected to the **HYDROGEN LASER**.
- The **HYDROGEN LASER** is connected to the **Receiver-Synthesizer**.
- The **Receiver-Synthesizer** is connected to the **Cycle Counter Discriminator & Event timer**.
- The **Cycle Counter Discriminator & Event timer** outputs a **Timing Pulse** to the **Photodetector**.
- The **Photodetector** is connected to the **Carrier Reflector**.
- The **Carrier Reflector** is connected to the **Time Readout**.
- The **Time Readout** is connected to the **TM & Command Inverter**.
- The **SPACECRAFT** section is also connected to the **Seismometer Telemetry & Command System**.

LASER RANGING STATION Section:

- The **Carrier Reflector** from the spacecraft is connected to the **Telescope & Photodetector**.
- The **Telescope & Photodetector** is connected to the **Event timer**.
- The **Event timer** is connected to the **Time Interval Recorder**.
- The **Time Interval Recorder** is connected to the **Station time**.
- The **Station time** is connected to the **W. Meter**.
- The **W. Meter** is connected to the **Pulse**.
- The **Pulse** is connected to the **Laser**.
- The **Laser** is connected to the **Telescope & Photodetector**.

Legend:

- Heavy lines indicate 100C components**
- Dashed lines indicate 100C components**

3. Experiment Overview

The main element of the HMC experiment is a hydrogen maser atomic clock that will be mounted on Mir, which is in a 350 km altitude orbit inclined at 51°. Time comparisons will be made with the laser ranging station at the NASA Goddard Space Flight Center. Laser pulses sent from the ranging station to the spacecraft will be reflected back to the ranging station by cube corner retroreflectors mounted on the spacecraft. A photodetector mounted with the retroreflectors will detect the arrival of a laser pulse at the spacecraft and will trigger an event timer that records the pulse's arrival time in terms of the spacecraft maser's time scale. The arrival time will be calculated, in terms of the earth-based time scale, from knowledge of the times of pulse transmission and of reception at the earth station. The goal is to understand the long term systematic effects of the space environment, with daily time comparisons at a level of about 80 picoseconds we can assess the frequency drift of the maser over 24 hours with a precision of 1 part in 10¹⁵, a precision that improves as the time interval increase.

4. Structural Overview

The HMC experiment will be delivered to Mir by the NASA shuttle. The experiment is mounted in a tubular structure to be secured on the Docking Module on Mir using a mechanical latching structure, as shown in Figure 3.

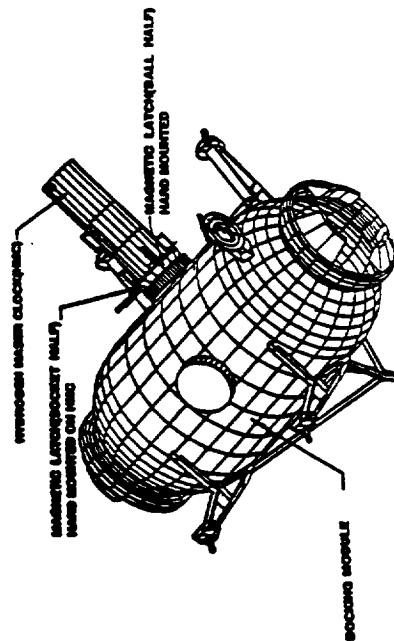


Figure 3. HMC attached to the Mir Docking Module

Power and data connection will be made to Mir by a single cable. Thermal control is done by radiation to space mitigated by a concentric array of by heat-added thermal controllers. The experiment configuration will be mounted to the "Get Away Special" (GAS) beam of the shuttle. The package consists of: (i) the hydrogen maser physics unit; (ii) the electronics required to interface with the spacecraft, operate the maser, and measure the arrival time of laser pulses; (iii) laser retroreflector/detector units that time the arrival of a laser pulse at the spacecraft and reflect the pulse back to the ranging station; (iv) a GPS receiver and (v) a silver zinc rechargeable battery system to maintain continuous operation for several hours in the event of power outages.

5. The Physics Package and its Vacuum System

The H maser oscillator shown in cross-section in Figure 4, consists of a microwave resonant cavity assembly and storage bulb, an RF dissociator that creates a beam of hydrogen atoms that are state selected and focused into the bulb by a hexapole permanent magnet, and vacuum pumps to remove expended hydrogen and other gases. These are all housed in a titanium and stainless steel vacuum envelope.

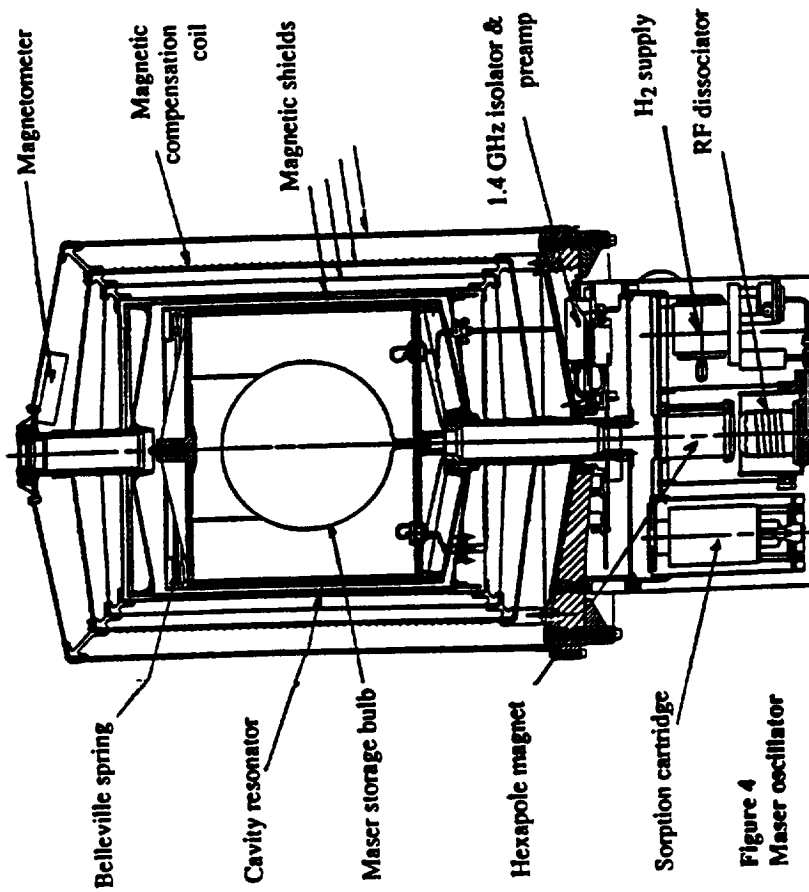


Figure 4
Maser oscillator

Expended hydrogen is absorbed by two sorption cartridges that capture only hydrogen. Two small ion pumps with self-contained high voltage supplies, remove other outgassing products.

The cylindrical vacuum tank, made of titanium alloy, contains a cylindrical TE011 mode microwave resonant cavity, within which is mounted a quartz hydrogen storage bulb. The cylinder and end plates of the resonator are made of internally silvered Cer-Vit, a mechanically stable glass-ceramic material having a very low thermal coefficient of expansion. A double Belleville spring clamps the cavity endplates to the cylinder with an axial force of approximately 480 lbs. It is adjusted so that the compressive force is nominally independent of the length of the hold-down can and thus the cavity's resonance frequency is approximately independent of the thermal expansion of the hold-down can. The cavity mounting baseplate is attached in cantilever at its center to the base of the vacuum tank for isolation from dimensional changes in the outer vacuum envelope.

The maser signal is picked up by a coupling loop at a level of approximately -100 dBm and sent through an isolator and amplifier to the receiver. A second loop within the cavity incorporates a reverse-biased varactor tuning diode to make small frequency adjustments to the cavity's resonance frequency.

The source of H_2 is about 50 grams of lithium aluminum hydride contained in a heated stainless steel container whose temperature is controlled to maintain a constant hydrogen pressure within the container. Hydrogen flow into the maser is controlled by permeation through a heated palladium silver diaphragm, sensing the pressure in the dissociator by means of a thermistor Pirani gauge, and regulating the diaphragm temperature.

Molecular hydrogen at a pressure of approximately 10^{-1} torr is led to a cylindrical glass bulb (~6 cm long \times 3 cm diameter) mounted within the vacuum chamber. A plasma discharge in the bulb is maintained by about 4 watts of 75 MHz RF power to dissociate molecular hydrogen. Atomic hydrogen is collimated into a beam of about 10^{14} H atoms per second into the state selection magnet that focuses atoms in the upper hyperfine quantum state into the storage bulb.

Frequency shifts from variation of the magnetic field within the maser storage bulb are controlled by 4 layers of passive shielding and by active field compensation. Leakage through the first shield is sensed by a flux-gate magnetometer and nulled by a compensating coil wound on the next innermost magnetic shield. This combination provides a shielding factor, $S = \Delta B_{ext}/\Delta B_{int} > 2 \times 10^6$, for external field variations of ± 0.5 Gauss. A two-layer flexible printed circuit solenoid closely fitted to the inside of the innermost shield produces a 0.5 milliGauss uniform axial magnetic field within the cavity. With the available shielding factor, we can limit the fractional frequency effect of external field variations to less than 1 part in 10^{15} .

The temperature dependence of the resonance frequency of the cavity bulb combination is about -800 Hz/degree C. In H-masers, the output frequency is "pulled" by the resonator variation by the ratio Q_{cavity}/Q_{atomic} line times the resonator shift. Our ratio is about 1.5×10^{-5} and to maintain stability at a level of 1 part in 10^{15} we require

temperature stability of 10^{-4} degrees C. The microprocessor controlled temperature servo that we have developed to do this is discussed in a separate paper at this meeting.¹

6. Timing and Tracking Equipment

Corrections for relativistic and gravitational effects are required in the frequency comparisons. The magnitude of the second order Doppler effect from relative motion is about -3.2×10^{-10} ; the gravitational red shift is $+5.06 \times 10^{-11}$. An on board GPS receiver will be used to obtain data to provide position accuracy at the 1 meter level and along-track velocity accuracy at 1 mm per second. This level of precision will allow a maximum fractional frequency error of about 2×10^{-16} . Timing data from the GPS receiver will also serve to identify the times (epochs) of the specific light pulse transmitted from the earth stations.

Laser pulses arriving at the spacecraft will be sensed and their arrival times will be recorded in terms of the time scale maintained by the space maser. Pulses will be reflected back to the ground station by the corner reflectors and their round-trip time interval will be recorded at the earth stations with a similar event timer. A complete account of the retroreflector detector event timer system is the topic of a separate paper at this meeting.²

Each retroreflector array contains twenty solid fused-quartz cube corners mounted in an aluminum housing along with an array of optical fibers that receive laser light and transmit it, via a fiber bundle a few centimeters long, to the optical filter and photodetector and event timer circuit enclosed in the same housing. The photo detector's output pulse goes to a constant-fraction discriminator and then to the event timer and recorded with a resolution of 10 picoseconds. Because the expected pulse length is considerably longer than the desired measurement precision of 10 ps, and the pulse height can vary from pulse to pulse, the constant-fraction discriminator circuit is needed to produce a logic pulse at a time that is largely independent of the laser pulse's amplitude.

Each event timer operates from a 100 MHz maser signal. The event timer consists of standard digital gates and registers, and a hybrid analog time interpolation circuit. The interpolator charges a capacitor by a constant-current source triggered by the incoming pulse, and discharges it at a slower rate through a second constant-current circuit. The discharge time is measured in terms of 10 ns clock periods, with the ratio of discharge-to-charge currents providing a 1000-to-1 "expansion" of time, thus yielding the 10 ps measurement resolution. Timing data from the GPS will also be recorded. Timing data will be sent to the HMC dedicated experiment processor for formatting with other data transmitted to earth.

7. Data Retrieval and Command

Data from the dedicated experiment processor will be stored using a specially modified IBM-750 C laptop computer located within the Mir cabin. Data will be recorded daily on a floppy disc and then transferred to the Mir Interface to Payload

System (MIPS-2) Controller and Optical Disc System for transmission to the Russian Space Agency's ground stations.

Standard digital circuitry provides the interface between the HMC and the spacecraft's telemetry and telecommand functions. The dedicated experiment computer buffers signals between the HMC and the spacecraft, receiving telecommands and sending data to the IBM 750C. Pre-recorded command sequences will be stored in the laptop for execution by keystroke entry by a Russian Cosmonaut. These commands include the maser power sequence, cavity resonator tuning, RF dissociator operating level, automated magnetic field measurement (Zeeman sweep) and functions for various diagnostic programs.

8. Summary of HMC Size Weight and Power

Physics Package--Cylindrical structure 43.1 cm dia. 83.9 cm long weighs 70.7 kg.
Electronics control box --30.5 x 30.5 x 33 cm and weighs 12 kg.
Maser receiver --16.5 x 15.2 x 12.7 cm and weighs 2.3 kg.
Experiment microprocessor--26.25 x 16 x 14 cm. and weighs 3.8 kg.
Reflector detector/event timers--2 X 2.5kg = 5 kg

Cabling and connectors--3.5 kg
Battery Unit--12.7 kg
Power Control Unit--3.6 kg
GPS receiver--3.4 kg
HMC Structure and thermal radiators--75.6kg

The entire experiment will consume on average approximately 156 to 188 watts of 28 VDC power, depending on thermal conditions owing to the orientation of Mir as it orbits the earth.

9. Status of the HMC program and Acknowledgements

Delivery of a flight-qualified system to the launch site at Kennedy Space Center is scheduled for January 1997. Integration in the Shuttle and installation on Mir is expected in October of 1997

The HMC contract is supported by NASA's George C. Marshall Space Flight Center, Huntsville, Alabama.

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- 1 E.M. Mattison, D. Boyd, L.M. Coyle and R.F.C. Vessot *Precise Temperature Control for Precision Frequency Standards* In these Proceedings
- 2 E.M. Mattison, L.M. Coyle, R.C. Smith and R.F.C. Vessot *A 10 ps Event Timer for Precise Time Transfer in Space* In these Proceedings

PRECISE TEMPERATURE CONTROL FOR PRECISION FREQUENCY STANDARDS

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ABSTRACT

We describe a high-efficiency precision temperature control system that has achieved temperature control in a hydrogen maser at the level of 10^{-4} °C. The system minimizes heat flow and temperature gradients by means of isothermal guard ovens and multiple control zones. Feedback control is provided by an integrating digital microcontroller and pulsewidth modulated heaters.

1. Precision Temperature Control

Variation in temperature can be a major contributor to systematic frequency variations in frequency standards. Most standards include a resonator whose dimensions are affected by temperature; in addition, frequency shifts due to atomic phenomena such as wall collisions, spin exchange, and the Doppler effect are functions of temperature. As a consequence, at least a portion of virtually all frequency standards must be controlled in temperature and shielded from changes in ambient temperature, generally by a combination of insulation and active heat-added electronic control circuits. The SAO/NASA Hydrogen Maser Clock experiment¹ aims to produce and test in space a hydrogen maser with a fractional frequency stability of $\sim 1 \times 10^{-15}$ /day. To achieve this goal the maser incorporates a physical design and an active temperature control system that maintains the 50°C temperature of the maser's resonant cavity and storage bulb – a cylindrical structure 31 cm in diameter by 36 cm long – constant at a level on the order of 10^{-4} °C. The main features of this system, which are described below, are applicable to a variety of precision temperature control problems.

2. Physical Design for Temperature Control

To enable the heat-added control system to operate, the maser's primary controlled structure – its cavity and the titanium vacuum tank that contains it – is maintained at an elevated temperature relative to the ambient, and is surrounded by three layers of thermal guard zones, as shown in cross-section in Figure 1. The innermost zone, which controls the vacuum tank, is maintained at 50°C; its three isothermal segments are the inner magnetic shield cylinder that surrounds the tank but is decoupled from it, and the inner ends of the tubular titanium necks that support the tank. The second zone, consisting of a three-section aluminum guard oven and the outer ends of the support necks, is at 40°C, controlled to about 0.1 °C or better. The circular midplane plate that supports the maser and connects it to the instrument's support structure is kept at about 30°C. Each zone element has one or more printed-circuit heaters, a control thermistor and a monitor ther-

mistor attached to its surface. The zones are configured to control all heat leakage paths, which result primarily from conductivity through the tubular titanium necks that support the vacuum tank and through the Delrin spacers that support the four concentric cylindrical magnetic shields that surround the tank, and from radiation radially between the shields.

Because the temperature of each zone is controlled only at the location of its control thermistor, changes in temperature gradients can cause heat flows that alter the temperature of the primary structure. Therefore it is important to minimize thermal gradients in the maser. Gradient reduction is achieved by eliminating power dissipation from the primary structure and by calibrating the measurement system. The vacuum tank does not dissipate power internally, and its temperature control zone is located on a magnetic shield that is decoupled from the tank. Careful calibration of the control thermistors reduces gradients between the nominally isothermal elements of each zone.

3. Electronic Controller

The maser's electronic control circuits are based on a commonly available digital microcontroller (μC) that incorporates a microprocessor and random access memory, an 8-channel analog multiplexer and an 8-bit analog-to-digital converter, and 24 digital outputs.² Five of the μC 's digital outputs are programmed as pulse-width modulated (PWM) outputs that control power transistors that feed the control zone heaters. PWM control provides the high power efficiency required by spacecraft power limitations. The period of the pulse width modulation is 0.52 seconds, much less than the maser's shortest thermal time constant. The circuit design contributes to temperature stability by eliminating the inherent temperature offset of purely proportional controllers by incorporating an integral term in the control algorithm. Because the thermal time constants of many of the maser's control zones are hours long, it is necessary to use digital techniques rather than analog circuits, which would require enormous capacitors. In addition, the digital capabilities of the μC allow us to adjust the control algorithm to match the thermal characteristics of each zone.

4. Measurements

The ability of the control system to stabilize the vacuum tank's temperature was measured by changing the temperatures of the forward neck and the maser support plate by approximately -2°C , in separate steps. (In practice, these zones are expected to be controlled on the order of 0.1°C .) The resulting changes in the temperatures of the tank control zones, all less than $3 \times 10^{-4}^\circ\text{C}$, are given in Table 1.

Table 1. Change in tank temperature due to change of adjacent zones

	$\Delta T_{\text{support}} = -2^\circ\text{C}$	$\Delta T_{\text{fwd neck}} = -2^\circ\text{C}$
$\Delta T(\text{Tank forward})$:	$-0.1 \times 10^{-4}^\circ\text{C}$	$+0.2 \times 10^{-4}^\circ\text{C}$
$\Delta T(\text{Tank cylinder})$:	$+1 \times 10^{-4}^\circ\text{C}$	$-1 \times 10^{-4}^\circ\text{C}$
$\Delta T(\text{Tank aft})$:	$+3 \times 10^{-4}^\circ\text{C}$	$-2 \times 10^{-4}^\circ\text{C}$

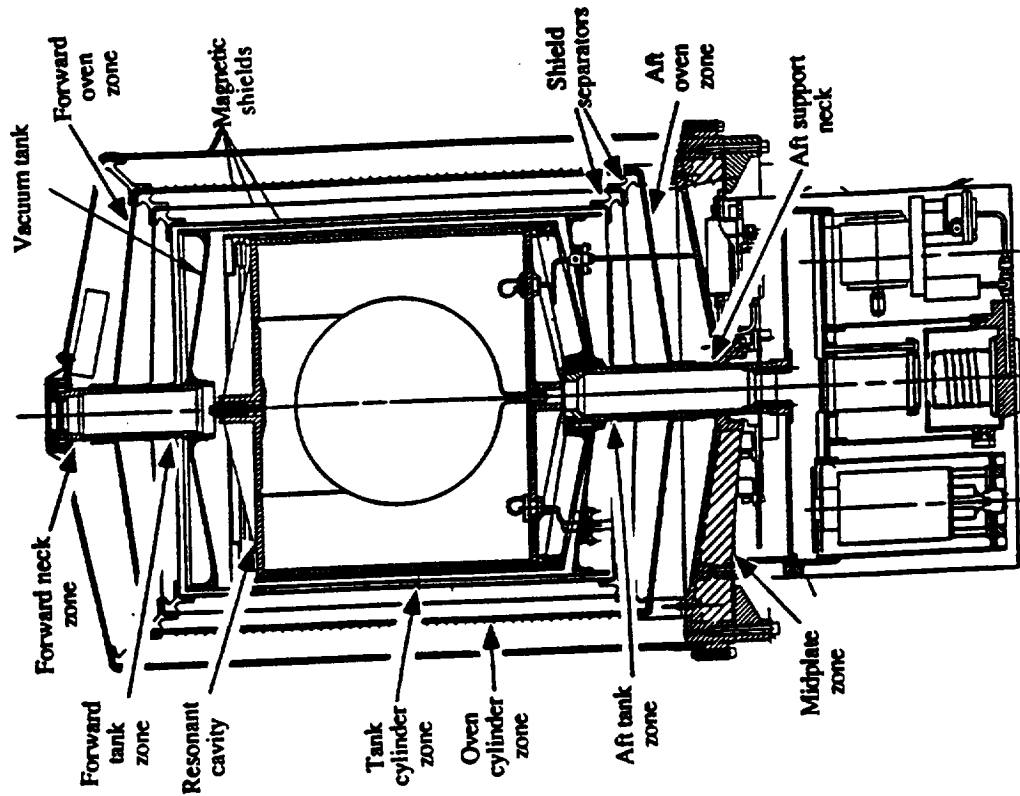


Figure 1. Cutaway view of hydrogen maser clock.

5. References

1. R.F.C. Vessot, E.M. Mattison, G.U. Nystrom, L.M. Coyle, D. Boyd, and T.E. Hoffman, "High precision time transfer to test an H-maser on Mir", these proceedings.
2. Motorola, Inc., 68HC11 microcontroller.

A 10 PS EVENT TIMER FOR PRECISE TIME TRANSFER IN SPACE

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ABSTRACT

We describe a space-qualified event timer system with a time resolution of 10 ps for use in space-based laser time transfer. The system incorporates three major components: a photomultiplier tube light sensor, a constant-fraction discriminator and a 10-ps time interpolator. The time interpolator has demonstrated exceptionally low time "walk," or variation with operational parameters. We present test data on the performance of the time interpolator, and describe its application to a space-based time-transfer experiment.

1. Time Transfer Technique

As part of the NASA/SAO Hydrogen Maser Clock (HMC) experiment,¹ we have developed a system for high-precision time transfer between space-borne and earth-based clocks, using laser pulse timing.² In this system time kept by a clock located at an earth-based laser ranging station (LRS) is compared with the space clock's time by measuring the arrival time of a laser pulse at the spacecraft in terms of both the space and earth time scales. A laser pulse transmitted from the LRS is detected at the spacecraft and its arrival time is determined in terms of the space clock's time by a high-speed electronic event timer. The pulse is also reflected by a retroreflector array mounted on the spacecraft and is received at the LRS as a return pulse. Its transmission and return times are measured in terms of the earth clock's time by an event timer located in the LRS. The measured earth and space times provide a comparison of the respective clock time scales.

The main components of the HMC time transfer system are the retroreflector array; an omnidirectional fiber-optic light collector; a photomultiplier tube and preamplifier; and the event timer, consisting of a constant-fraction discriminator and a time interpolation circuit (TIM) with a resolution of 10 ps. The space-qualified TIM, which has exhibited excellent repeatability and low systematic variation of measured time, is useful for a variety of precise space and earth timing applications.

2. Retroreflector Array and Fiber-optic Light Collector

The HMC retroreflector array consists of 20 fused silica cube corners, each 1 cm in diameter, mounted in a hemispherical base. This shape provides a hemispherical field of view, permitting reflections independent of spacecraft attitude. Laser pulses impinging on the retroreflector array are brought to a photomultiplier tube by an omnidirectional

fiber optic light collector. The collector consists of a 22-cm long bundle of 127 optical fibers, each 100 μm in diameter. At one end of the bundle the fibers are splayed out into a hemispherical pattern and inserted through holes drilled in a 1.5-cm diameter hemispherical shell that is mounted at the apex of the retroreflector array. The hemispherical fiber array ensures that at least one fiber is illuminated by light coming from anywhere in a hemispherical field of view. The other end of the fiber bundle connects to a photomultiplier tube (PMT) that detects the laser pulses.

3. Event Timer

The time transfer system's ability to resolve sub-nanosecond intervals results from a high-precision space-qualified event timer developed at the Los Alamos National Laboratory that is capable of timing with a resolution of 10 ps. The output pulse from the PMT's preamplifier is sent to a constant-fraction discriminator (CFD), which produces a pulse whose shape is largely independent of the input pulse amplitude.^{3,5} This property of the CFD reduces the variation in triggering time that would otherwise result from the orders-of-magnitude variation in laser pulse intensity that can result from changes in atmospheric conditions and in spacecraft attitude and altitude.

The CFD's output pulse goes to the time interpolator,^{6,7} which is a combined digital and analog hybrid circuit that has the effect of subdividing the period of a 100 MHz clock signal by a factor of 1000. When a pulse triggers the time interpolator, a constant current I_c charges a capacitor until the next clock edge arrives. The capacitor is then discharged by a second constant current $I_d = I_c/1000$, and the discharge time is measured in terms of clock periods. By this technique the interpolator divides the 10 ns clock period into 1000 "bins", providing 10 ps resolution.

We have built and tested engineering models of the photomultiplier and event timer circuits. Measurements of the interpolator's integral linearity, which measures the total timing error for any bin compared to a perfectly linear interpolator, are shown in Figure 1. The maximum excursion of the integral linearity is less than 10 ps, with test-to-test repeatability of less than 1 ps, and variation of less than 5 ps in any bin from 10°C to 30°C. The resulting systematic variations in measured time are repeatable and can be calibrated to a few picoseconds.

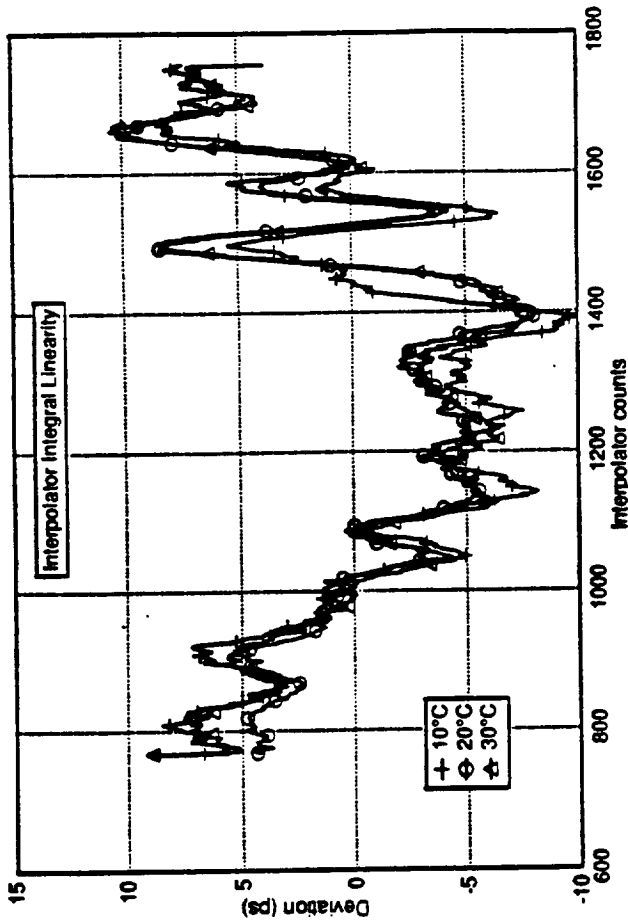


Fig. 1. Integral Linearity of Engineering Model Time Interpolator

4. Acknowledgment

This work is supported by the George C. Marshall Space Flight Center, Huntsville Alabama.

5. References

1. R.F.C. Vessot, E.M. Mattison, G.U. Nystrom, L.M. Coyle, D. Boyd and T.E. Hoffman, "High precision time transfer to test an H-maser on Mir", these proceedings.
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DESIGN OF A HYDROGEN MASER FOR SPACE

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1. ABSTRACT

An active atomic hydrogen maser for long-term use in space has been designed and built as part of the Smithsonian Astrophysical Observatory's Hydrogen Maser Clock (HMC) project. We describe aspects of the maser's mechanical, magnetic and thermal design that are important to its performance in space. The flight hardware has been tested in a laboratory thermal/vacuum chamber; we report performance measurements of the magnetic and thermal control systems.

Keywords: hydrogen maser, atomic clock, thermal control

2. CLOCKS IN SPACE; THE HYDROGEN MASER CLOCK PROGRAM

Frequency references – high stability clocks – increasingly find applications in space missions. Atomic clocks of ever increasing stability have present and potential uses as frequency references for the GLONASS and Global Positioning System navigation systems, local oscillators for space-based Very Long Baseline Interferometry, "proper" clocks for tests of general relativity, frequency references for detection of gravitational radiation, and "traveling clocks" for worldwide time transfer.

Clocks for use in space must satisfy several restrictions and requirements, many of which are also requirements or desirable features of earth-based clocks. These requirements include:

- Limitations on mass, size and power
- Requirements for reliable long-term unattended operation
- Ability to withstand vibrational loads during launch
- Ability to tolerate varying magnetic fields
- Ability to cope with a varying thermal environment

An active atomic hydrogen maser for long-term use in space has been designed and built as part of the Smithsonian Astrophysical Observatory's Hydrogen Maser Clock (HMC) project. HMC is a NASA-sponsored program with the goal of producing and demonstrating a space-qualified hydrogen maser with drift-removed fractional frequency stability of 10^{-15} or better in one day. The HMC maser is an evolutionary outgrowth of a two-decade long SAO program of research and development of hydrogen masers for earth and space use.^{1,2,3} The maser and its control electronics have been designed as an integrated system to cope with the requirements of space flight. We discuss below characteristics of its mechanical, magnetic and thermal design that are particularly relevant to use in space.

The HMC maser is designed for use with a variety of spacecraft, requiring only an appropriate mechanical connection and electrical interface. It was originally to be tested aboard the European Space Agency's Eureka spacecraft, and then, following cancellation of the planned Eureka reflight, on the Russian Mir space station⁴. At present the flight portion of the HMC program has been

terminated, and the flight model maser and its electronics are undergoing laboratory testing at SAO.

3. MECHANICAL AND STRUCTURAL CHARACTERISTICS

The HMC maser's physics unit, shown in cross-section in Figures 1 and 2, takes the general form of a cylinder with 84 cm long and 43 cm in diameter. The maser's main components are its quartz storage bulb and low-expansion resonant cavity; the titanium vacuum tank that contains the cavity; a stainless steel vacuum manifold that includes two sorption pumps for scavenging hydrogen and two small ion pumps for removing other gases; a LiAlH_4 hydrogen source and a glass dissociator chamber for producing a beam of hydrogen atoms; electrical heaters, insulation and thermistors for temperature control; and magnetic shields and solenoids for magnetic field control. In addition, the physics unit contains electronic components that amplify the 1420 MHz maser signal from the cavity and electrically isolate the cavity from external perturbations. Separate units contain analog and digital control and monitoring electronics, the R.F. receiver that phase-locks a 100 MHz crystal oscillator to the maser signal, and a microprocessor that controls the maser's electronics and acts as an interface with the spacecraft's data and telecommand system. The masses of the major instrument elements are given in Table 1. Additional elements, whose masses depend upon the specific spacecraft used, are the bracket that mounts the maser to the spacecraft, and any additional spacecraft-specific electronics.

Table 1. HMC Instrument Mass Summary

Element	Mass (kg)
Maser physics unit	70.7
Control and RF electronics	27.9

Structurally, the maser is supported from a circular aluminum midplane plate, which supports the maser's resonant cavity and vacuum tank on one side, and its vacuum manifold and hydrogen source on the other. The midplane plate is the main structure for mounting the maser to the spacecraft. A titanium "aft neck" tube connects one end of the vacuum tank to the midplane plate and the vacuum manifold, while a similar "forward neck" connects the other end of the vacuum tank to the maser's cylindrical outer aluminum housing. The housing, in turn, transfers the forward neck's load to the midplane plate. By means of an ANSYS finite element model with approximately 2800 nodes, the HMC maser has been designed to cope with the vibrational and accelerational loads of a Space Shuttle launch. It can withstand at least 15 g's r.m.s., in all axes acting simultaneously, in a spectrum from 20 Hz to 2 kHz. The maser's lowest mechanical resonant frequency is 46 Hz. The flight cavity and vacuum tank, which are the most critical components, have been tested to flight input vibrational levels.

4. MAGNETIC FIELD CONTROL

A spacecraft in low earth orbit experiences the earth's magnetic field, with a magnitude of about 0.5 gauss and a variation over an orbit of up to ± 0.5 gauss, depending upon the spacecraft's attitude in orbit. In addition, some spacecraft create variable magnetic fields themselves, for example by magnetic torquers used for attitude control. The magnetic field within the maser's storage bulb must be maintained at a level on the order of 0.3 milligauss. To achieve frequency stability of better than $\Delta f/f < 1 \times 10^{-15}$, the temporal variation of the internal magnetic field must be less than $\Delta H < 0.8 \times 10^{-6}$ gauss. To achieve these conditions the HMC maser utilizes passive magnetic shields, internal solenoids and an active magnetic compensation system.

As shown in Figure 1, the maser's resonant cavity and titanium vacuum tank are surrounded by a three-section, two-layer cylindrical printed circuit solenoid that creates the internal magnetic field of approximately 0.3 milligauss, and by four layers of concentric magnetic shields that attenuate external fields. The outermost shield extends to enclose the vacuum pump manifold and atomic hydrogen dissociator, reducing external fields that could perturb the state-selected atomic hydrogen beam. The measured shielding factor of these Hypemom shields is

$$S_{\text{passive}} = \frac{\Delta H_{\text{ext}}}{\Delta H_{\text{int}}} = 3.4 \times 10^5$$

The passive shields are augmented by an active magnetic compensation system. A single-axis fluxgate magnetometer sensor is mounted inside the outer shield to sense the axial field near the end of the maser. A compensation coil is wound on the outside cylindrical surface of the next shield, and a feedback circuit drives the coil to keep the field sensed by the magnetometer constant. The shielding factor for the total magnetic control system, determined by measuring the transverse ("Zeeman") resonance frequency in the oscillating maser storage bulb, is

$$S_{\text{total}} = 2.8 \times 10^6$$

With this shielding factor, the expected maximum fractional frequency variation due to movement through the earth's field is on the order of $\Delta f/f \sim 2 \times 10^{-16}$.

5. THERMAL CONTROL SYSTEM DESIGN FEATURES

Temperature changes of the maser's resonant cavity and storage bulb affect the maser's output frequency. To keep frequency variations below the level of 1 part in 10^{15} , the cavity temperature must be maintained constant to approximately 10^{-4} °C. The HMC maser employs several strategies to achieve this level of temperature control. To control heat flow from the vacuum tank, the maser's structure is divided into three concentric isothermal control regions. Thermal gradients are controlled by subdividing each isothermal region into multiple independently controlled zones, by mounting controlled guard heaters on heat leakage paths, by separating heaters from the primary controlled structure (the vacuum tank) and by carefully calibrating and matching thermistors and setpoint resistors to ensure that all zones of an isothermal region control at the same temperature. Radiative heat flow is

reduced by means of multilayer insulation in the spaces between the regions, which are evacuated by being open to the space environment, while conductive heat flow is controlled by design of the segmented nylon rings that support the magnetic shields.

As shown in Figure 2, the innermost isothermal region, which is the titanium vacuum tank that surrounds the resonant cavity, is maintained at 50°C. The resolution of the tank control system is 1×10^{-4} degrees. To reduce thermal gradients in the tank, the three tank heaters are separate from the tank itself, one being located on the outside surface of the inner magnetic shield that is directly outside the tank and the others on the titanium neck tubes where they connect to either end of the tank.

The tank, in turn, is surrounded by an aluminum oven that is located directly over the third magnetic shield and whose temperature is maintained at 41°C. The oven region acts as a guard to control heat that flows from the tank region both radiatively from the tank surface and conductively along the magnetic shield supports and the titanium support necks. The oven region consists of three control zones located on the cylinder and end surfaces of the oven, and two zones mounted on the outer ends of the support necks.

The third isothermal region consists of the midplane plate and an outer aluminum support shell that directly surrounds the fourth magnetic shield. This zone is maintained at approximately 27°C by a control thermistor and set of heaters mounted on the midplane plate.

In addition to the thermal control zones that are integral with the maser, the system includes a controlled temperature guard station on the structure that mounts the maser to the spacecraft, to act as a first stage of isolation from the conductive environment. The entire instrument is surrounded with multilayer insulation to isolate it from the radiative environment.

The thermal control system incorporates several electronic and hardware features to achieve the high degree of thermal stability required. The digital electronic control system is based upon four 68HC11 microcontrollers, each of which can control up to five thermal zones. Each 68HC11 includes a microprocessor, an 8-bit analog-to-digital converter with eight-channel multiplexer, and timer registers that are used as pulse-width modulators (PWM) for high-efficiency switched heater power control. The vacuum tank heaters, which are closest to the maser's resonant cavity, are powered by high-frequency (~8 kHz) PWMs to avoid perturbation of the maser oscillation; the other heaters are switched at a 6 Hz rate. The thermal control program incorporates a three-mode PID (proportional, integral and differential) algorithm to eliminate proportional offset. (Differential control is included in the algorithm, but has not been found to be useful in this application.)

Components of the thermal control system have been chosen for thermal stability and low magnetic field production. Thermistors are glass-encapsulated, high stability units that have been burned in. Monitor and control thermistors for each zone are chosen to be matched. Temperature setpoint resistors are chosen to have low temperature coefficients, and are physically mounted on a temperature controlled zone within the maser for minimum temperature perturbation. Heaters are flexible printed circuits with Kapton film insulation. For each heater identical

etched foil elements are overlayed with opposite current flow, to minimize magnetic field production.

The ability of the thermal control system to stabilize the tank zone temperatures in the face of external temperature changes is shown by the data of Table 2. For these measurements, which were made on the engineering model of the maser, the temperatures of the maser support structure and the forward neck guard zone were separately lowered by 2°C.

Table 2. Response of tank control zones to external temperature change		
	$\Delta T(\text{Support}) = -2^\circ\text{C}$	$\Delta T(\text{Fwd neck}) = -2^\circ\text{C}$
$\Delta T(\text{Tank forward}):$	$-0.1 \times 10^{-4}^\circ\text{C}$	$+0.2 \times 10^{-4}^\circ\text{C}$
$\Delta T(\text{Tank cylinder}):$	$+1 \times 10^{-4}^\circ\text{C}$	$-1 \times 10^{-4}^\circ\text{C}$
$\Delta T(\text{Tank aft}):$	$+3 \times 10^{-4}^\circ\text{C}$	$-2 \times 10^{-4}^\circ\text{C}$

6. PRELIMINARY TEST RESULTS

The maser physics package has been operated in a thermal-vacuum tank continuously since August 1996. Analysis of the data under varying degrees of thermal perturbation is still in process and will be reported in a future journal. From a rough evaluation we can say that the immunity of the maser to thermal and magnetic environmental changes is well within specifications.

A plot of the measured frequency stability data is shown in Figure 3.

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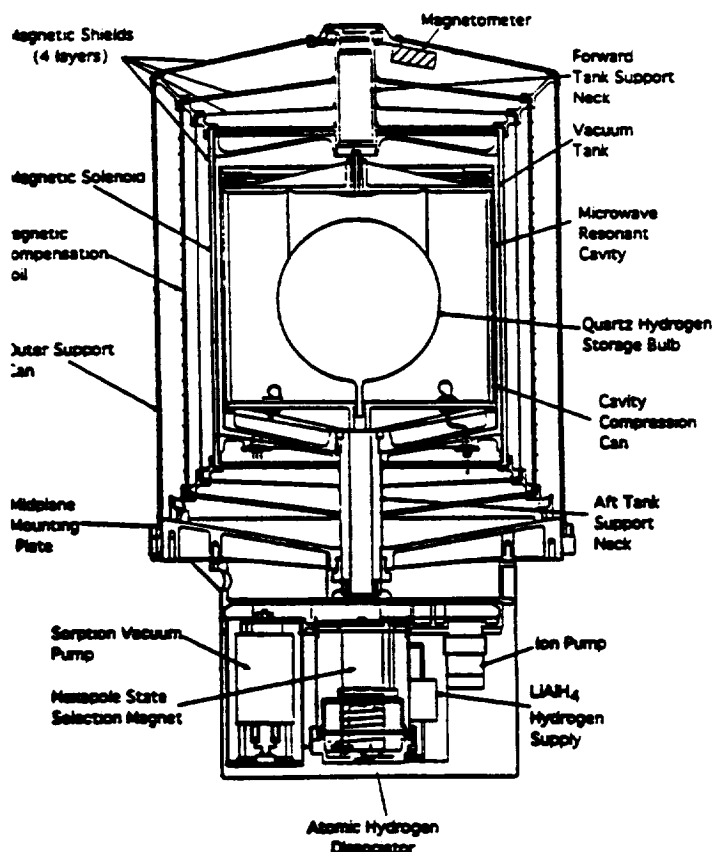


Figure 1. HMC maser - major components

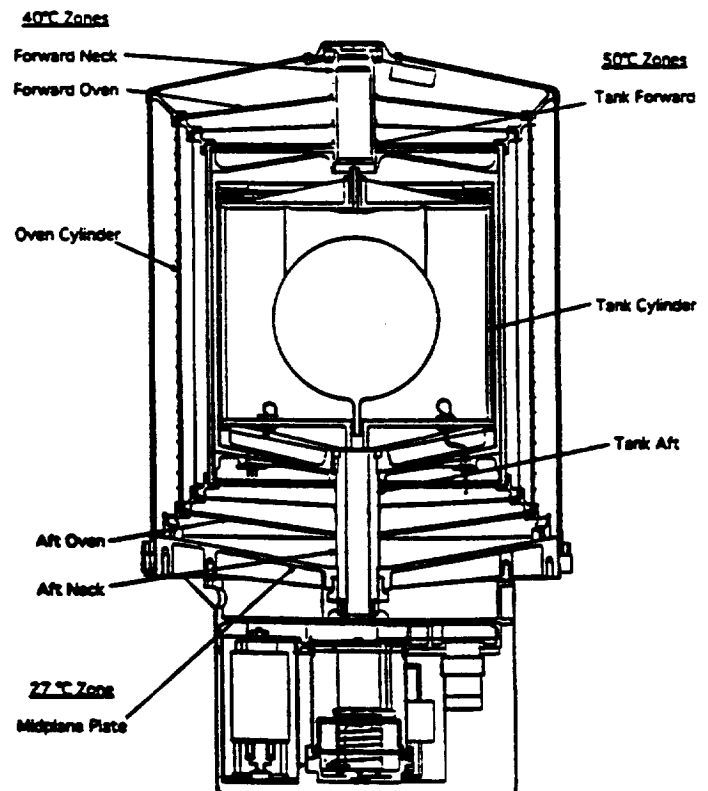


Figure 2. Thermal Control Zone Locations

MILLI-CELSIUS-STABILITY THERMAL CONTROL FOR AN ORBITING FREQUENCY STANDARD

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ABSTRACT

The Hydrogen Maser Clock (HMC) will provide a frequency standard in near-earth orbit with stability of one part in 10^{15} over a day. Originally scheduled for launch on EURECA, the flight-model HMC requires only mechanical interface adapters and access to a heat sink to operate on a wide variety of space platforms.

Because the oscillation frequency of the hydrogen maser at the core of the experiment is a strong function of temperature, control of the maser to about 10^{-4} °C is required to achieve the needed stability. This paper addresses co-evolution of both thermal design configuration and feedback control system design. Thermal design details presented include choice of materials and heat flow paths, placement of sensors and heaters, thermal gradient control, and effects of thermal response time. The controller design discussion incorporates bridge amplifier stability, effect of analog-to-digital quantizing, multi-zone microprocessor thermal control, and tuning the system for performance. Finally, we discuss testing of engineering and flight instruments to demonstrate successful control over a range of external environment changes.

INTRODUCTION

Frequency references – high stability clocks – increasingly find applications in space missions. Atomic clocks of ever increasing stability have present and potential uses as frequency references for the Global Positioning System navigation system, local oscillators for space-based Very Long Baseline Interferometry, "proper" clocks for tests of general relativity, frequency references for detection of gravitational radiation, and "traveling clocks" for worldwide time transfer.

Clocks for use in space must satisfy several restrictions and requirements, many of which are also desirable features of earth-based clocks:

- Limitations on mass, size and power
- Need for reliable long-term unattended operation
- Ability to withstand vibrational loads during launch
- Ability to tolerate varying magnetic fields
- Ability to cope with a varying thermal environment.

An active atomic hydrogen maser for long-term use in space has been designed and built as part of the Smithsonian Astrophysical Observatory's Hydrogen Maser Clock (HMC) project. HMC is a NASA-sponsored program whose goal is to produce and demonstrate a space-qualified hydrogen maser with drift-removed fractional frequency stability of 10^{-15} or better in one day. The HMC maser is an evolutionary outgrowth of a two-decade long SAO program of research and development of hydrogen masers for earth and space use. The maser and its control electronics have been designed as an integrated system to cope with the requirements of space flight. We discuss below characteristics of its mechanical, magnetic and thermal design that are particularly relevant to use in space.

The HMC maser is designed for use with a variety of spacecraft, requiring only an appropriate mechanical connection and electrical interface. It was originally to be tested aboard ESA's EURECA spacecraft (Figure 1); then, following cancellation of the planned EURECA refight, on the Russian MIR space station. At present the flight model maser and its electronics are undergoing laboratory testing at SAO.

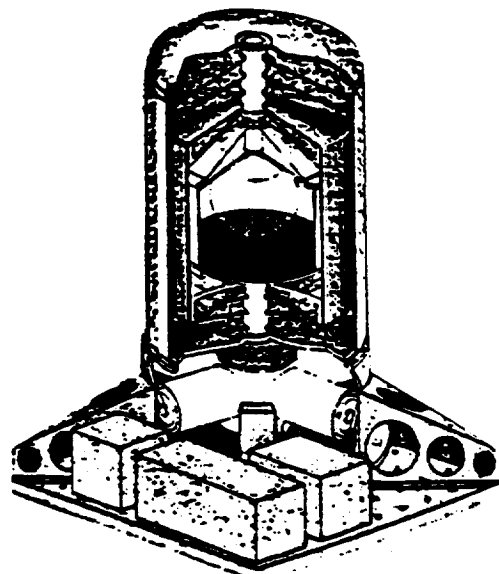


Figure 1: HMC configured for EURECA

MECHANICAL / STRUCTURAL CHARACTERISTICS

The HMC maser's physics unit, shown in cross-section in figures 1 and 2, takes the general form of a cylinder of 84 cm length and 43 cm diameter. The maser's main components are its quartz storage bulb and low-expansion resonant cavity; the titanium vacuum tank that contains the cavity; vacuum manifold and source for producing a beam of hydrogen atoms; electrical heaters and thermistors for thermal control; and components for magnetic field control. Separate electronics units contain analog and digital control and monitoring circuits and a microprocessor that controls the maser's electronics and acts as an interface with the spacecraft's data and telecommand system.

The maser is supported structurally from a circular aluminum midplane plate, with the maser's resonant cavity and vacuum tank on one side and its vacuum manifold and hydrogen source on the other. The midplane plate is the main structure for mounting the maser to the spacecraft. Two titanium tubes connect the vacuum tank to the midplane plate at the bottom end and to the maser's cylindrical outer aluminum housing at the top. The housing, in turn, transfers the upper tube's load to the midplane plate.

THERMAL CONTROL SYSTEM DESIGN FEATURES

Temperature changes of the maser's resonant cavity and storage bulb affect the maser's output frequency. To stabilize frequency the cavity temperature must be maintained constant to approximately 10^{-4}°C over a day. The HMC maser employs several strategies to achieve this level of temperature control. The integrated system is of particular interest because it embodies a large

number of elements that are common to precision active thermal control for the space environment. To control heat flow from the vacuum tank, the maser's structure is divided into three concentric isothermal control regions. Each region establishes the external environment for the next-inner region. Assuming the external environment to vary roughly $\pm 10^{\circ}\text{C}$, each control zone must attenuate this variation by a factor of 50 to achieve the desired accuracy of maser thermal control. Thermal gradients are controlled by subdividing each isothermal region into multiple independently controlled zones, by mounting controlled guard heaters on heat leakage paths, by separating heaters from the primary controlled structure (the vacuum tank) and by carefully calibrating and matching thermistors and setpoint resistors to ensure that all zones of an isothermal region control at the same temperature. Radiative heat flow is controlled by surface emittances and selective use of multilayer insulation in the evacuated annular spaces between the regions, while conductive heat flow is controlled by design of the segmented nylon magnetic shield support rings and interface materials and bolting pressures.

The control system configuration is entirely axial and radial; no side-to-side or circumferential control is used. External multilayer insulation is adequate to isolate the package from an enclosed environment such as that of EURECA. For the MIR mission the HMC was mounted within and radiatively isolated from a structural cylinder. Four circumferential control zones were added to the circular mechanical mounting flange to attenuate the asymmetric effects of external exposure to the space environment.

As shown in Figure 2, the innermost isothermal region, which is the titanium vacuum tank that surrounds the resonant cavity, is maintained at 50°C . The resolution of the tank control system is 10^{-4}°C . To reduce thermal gradients in the tank, the three tank heaters are separate from the tank itself, one being located on the outside surface of the inner magnetic shield that is directly outside the tank and the others on the titanium tubes where they support either end of the tank.

The tank, in turn, is surrounded by a 40°C aluminum shell that is located directly over the third magnetic shield. This oven region acts as a guard to control heat that flows from the tank region both radiatively from the tank surface and conductively along the magnetic shield supports and the titanium support necks. The oven region consists of three control zones located on the cylinder and two end surfaces of the oven, and two zones mounted on the outer ends of the support necks.

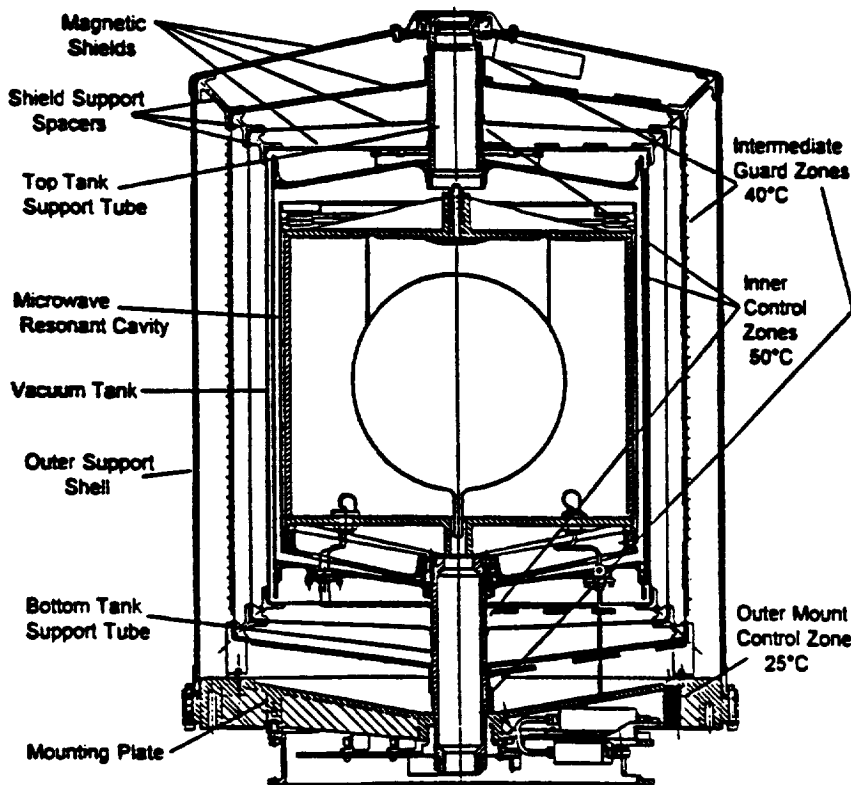


Figure 2. Design elements and thermal control zones in the HMC

The third isothermal region consists of the midplane plate and an outer aluminum support shell that directly surrounds the fourth magnetic shield. This zone is maintained at approximately 25°C by a control thermistor and heaters mounted on the midplane plate.

In addition to the thermal control zones that are integral with the maser, the system includes a controlled temperature guard station on the structure that mounts the maser to the spacecraft, to act as a first stage of isolation from the conductive environment. The entire instrument is surrounded with multilayer insulation to isolate it from the radiative environment.

Early tradeoff studies established the major design choices in the thermal control system. Highly-stable thermistors were chosen over wirewound thermal sensors to minimize effects of lead-wire resistance. Each zone has two identical thermistors, one for control and one for monitoring (which can replace the control unit if necessary). Proportional/integral control was selected to eliminate proportional-offset control error, and digital control was picked over the more conventional analog to decrease thermal effects on controller circuits and for ease in modifying loop gains and time constants. Kapton-insulated etched-foil heaters were chosen to reduce magnetic effects; in critical regions a special-design sandwich of two identical elements with opposing currents was needed to ensure the lowest possible magnetic-field generation.

The thermal control system incorporates several electronic and hardware features to achieve the high degree of thermal stability required. The digital electronic control system is based upon 68HC11 microcontrollers, each of which can control up to five thermal zones. Each 68HC11 includes a micro-processor, an 8-bit analog-to-digital converter with eight-channel multiplexer, and timer registers that are used as pulse-width modulators driving a power stage for high-efficiency switched heater power control. The vacuum tank heaters closest to the maser's resonant cavity are driven at high frequency (4 kHz) to avoid perturbation of the maser oscillation; the other heaters are switched at a 30 Hz rate. The thermal control program provides for differential control as well, but this additional algorithm term is primarily useful in startup dynamics and has been found unnecessary. Temperature setpoint resistors have low temperature coefficients, and are physically mounted on a temperature-controlled zone within the maser for minimum temperature perturbation.

HIGH-PRECISION CONTROL CONSIDERATIONS

Thermal control at milli-Celsius levels requires integrated design of thermal, mechanical and electronic hardware. Effects that are negligible in conventional thermal control must be addressed systematically and their impacts allocated and traded for performance. Figure 3 shows a schematic of the control system with the most important effects shown as bullets. It is useful to discuss some of the important issues that apply to a wider class of high-precision control systems, especially under digital control:

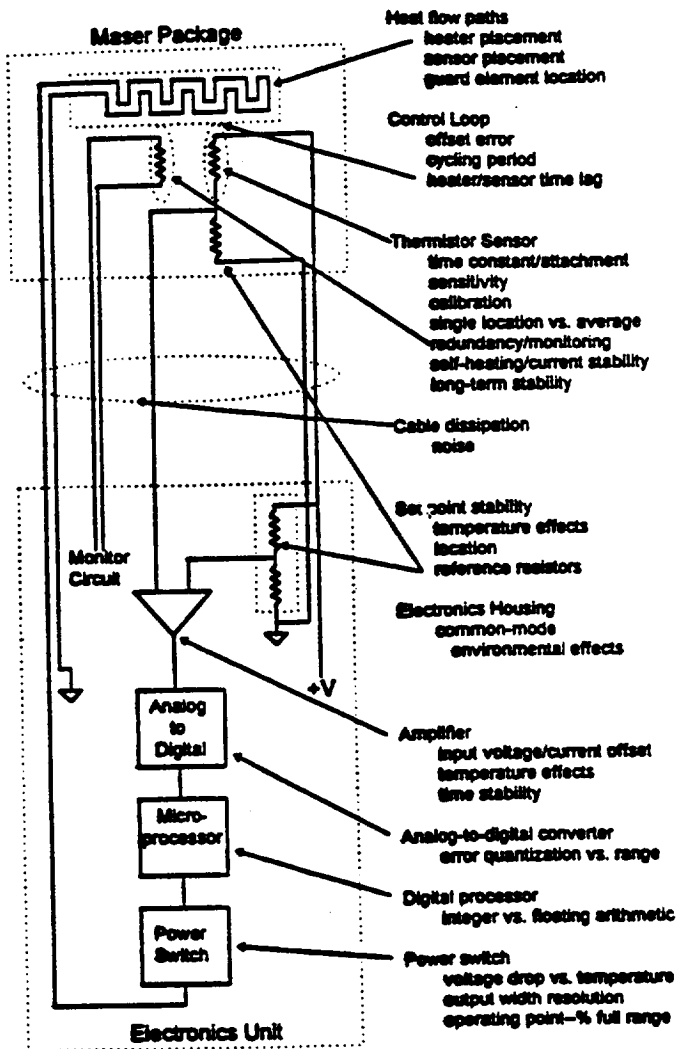


Figure 3: Control System Design Considerations

Control Loop: The offset error can usually be controlled by integral compensation, except during transients. It is important to use an algorithm that does not increment the integral when the temperature error is large, certainly not beyond the proportional band. The cycling period and heater/sensor time lag are closely related; the control sensor should be located as near the heater as possible, especially on poorly-conducting substrates. It is preferable to separate the natural cycling frequencies of adjacent zones to prevent interaction.

Heater power and location: Good practice dictates that the heater should be well-matched to the power requirement, but this is particularly true when the driving voltage is pulse-width modulated digitally. If, for example, the pulse width has 256 possible values, a heater operating at 50% duty cycle has a minimum power change of just under 1%. If the heater is oversized so that it operates at 8% duty cycle the minimum power resolution is about 5%. This raises the effective system gain and can cause hunting or cycling. Heaters should be located so that power changes in response to the control loop do not induce thermal gradients in the most critical control zones; heat should flow primarily outward from each heater.

Sensor: Sensors were individually calibrated in an oven at the control temperature so that the set points could be corrected to minimize gradients in the vacuum tank zones. If sensors are well-matched, averaging more than one may be effective. On HMC two identical sensors were installed side-by-side for redundancy; one was used for independent monitoring of zone temperature, but could be used for control in case of failure. Self-heating is significant—we measured the self-heating constant of sensors cemented to the controlled surface as about 0.15°C/milliwatt, and operated them at about 0.3milliwatt. This yields a self-heat temperature rise of 0.05°C, which means that the current stability in the sensor must be good enough that self-heating changes are much smaller than the control resolution. In the future we would consider using narrow current pulses for sensors to reduce self-heating. Also, the sensor time constant was a significant contributor to the natural frequency in the HMC control loops.

Reference elements: At the milli-Celsius level, temperature effects on the fixed resistors in the control bridge can be significant. HMC located the set point resistors in one of the controlled zones, and used a single-substrate matched resistor pair in the electronics unit for the other side of the bridge.

Cables can produce significant noise with microvolt-level signals. Noise is evident on the low-level error data shown in a later section, and makes monitoring difficult. Shielding can be effective but wiring in inner parts of the HMC left no space for it. Noise is not necessarily bad in the control loop as long as it averages to zero—but there is seldom assurance of this.

The instrumentation amplifier can have an input voltage/current offset that is temperature dependent, and that impresses electronics unit temperature changes on the control circuit. Careful design is needed; using a pulse train on the temperature-sensing bridge may also eliminate the problem.

The analog-to-digital converter creates a fundamental tradeoff in design: resolution versus range. HMC used an 8-bit A-to-D (256 values) in the control loop, so that for a minimum resolution of 0.0001°C, the total range was only 0.025°C. This implies a very high gain; dynamic control is a potential problem, and control points must be set very carefully. We may incorporate in future units a variable gain: high near the set point for good resolution and lower elsewhere for increased range.

The digital processor has a choice of integer vs. floating arithmetic. Integer arithmetic is faster and uses less memory, but control algorithms must be developed carefully to ensure that critical information is not lost in truncation. The transistor power switch has a voltage drop that is temperature-sensitive. An increase in switch temperature decreases voltage to the zone heater, requiring the control system to compensate. The same effect would occur with a variable bus voltage. It is usually best to remove as many disturbances as possible, especially for high-gain loops. We considered (but did not incorporate) a secondary loop to compensate for heater voltage; this could be important for a system with wider voltage changes.

THERMAL MODEL

A thermal mathematical model of about 100 nodes supported design and test of the HMC. This model's purpose was twofold: prediction of heater power requirements (rather than temperatures, which were controlled) for each of the zones so that adequate control margins could be established, and study of small changes in design parameters (heater location, for example) to minimize critical gradients. The model, like the control zone configuration, had only axial and radial detail. Each concentric shell—vacuum tank, magnetic shields, oven and outer shell—was divided into six zones axially and three radially (each end). Individual surface emittances were maintained as independent parameters so that they could be used to "tune" the heat flow paths.

Modeling the conductive paths was particularly difficult because of the large number of contact resistances with low interface pressures. The magnetic shields, for example, have end caps that are a slip fit over the cylinders, and the surfaces have low measured emittance. These shields are held in place with padded nylon spacers because the strains induced by conventional fasteners would affect shielding properties. Interfaces between the titanium support tubes and the top and bottom structural supports, two primary heat flow paths, have very small areas and insulating spacers. The top support tube interface was in fact the primary area of disagreement between model and hardware. Thermal isolation in this path was considerably greater than expected, effectiveness of that guard heater was less than desirable, and the top oven guard power was therefore increased.

Table 1 indicates predicted and actual heater power and installed capacity for each zone. Control power predictions are acceptably close to measured values, indicating that use of the model to minimize heat flow and gradients in each zone was probably successful. Operating a control zone in the steady-state condition at about 1/3 to 1/2 of its maximum range is desirable to allow upside and downside control margins and warmup capability, and we achieved this goal for most control zones. The design provided for a choice of two voltage levels to drive the most critical zones in case predictions were greatly in error. Two zone heater voltages were changed after initial test: the upper guard tube voltage was decreased because of the high thermal resistance path discussed above, and that of the tank radial zone increased because measured power had little margin.

Table 1. Predicted, actual and maximum control power

Control zone:	Heater power (watts)		
	predicted	actual	max
support guard top	2.1	0.8	1.7 6-6
vacuum tank top	0.5	0.4	1.5
vacuum tank radial	0.8	1.1	5.8 4-3
vacuum tank bottom	0.9	0.8	1.5
oven guard top	0.2	0.6	2.5
oven guard radial	1.4	2.9	4.2
oven guard bottom	2.0	1.9	2.5
support guard bottom	4.0	2.6	6.6

TUNING AND EXPERIMENTAL VERIFICATION OF THERMAL DESIGN

The experimental portion of the HMC program had the dual goals of tuning the individual zones for best control performance, and then evaluating both thermal performance and frequency of the clock under reasonable changes in external environments. Both were conducted in a vacuum tank because gas conduction effects would produce very different control results at ambient conditions. Changes in both radiative environment on the outer shell MLI and conductive sink temperature were expected in the mission so two fluid loops were incorporated in the test fixture, one surrounding the shell and the second at the mounting interface. In a near-earth mission environment these environment changes would have a primary period of about 1.5 hours, which was difficult to simulate in the laboratory, so the primary focus was on the more severe case of measuring step response and inferring control performance from those measurements. This test was regarded as a reasonable simulation of a carrier vehicle maneuver that could significantly change solar exposure, for example.

The control loops were tuned using a classical method [1], which requires removing all integral/differential compensation and increasing linear loop gain until temperature oscillates at a constant amplitude. Gain is then reduced and integral compensation added in a related amount to produce a slightly underdamped response to a step change. We observed control response according to a classical rule-of-thumb, which states that the primary oscillation is usually determined by the shortest lag or time constant in the system. Most of the high-gain loops oscillated with a 5-10 second period, which is likely related to the thermal lag between the heater mats and the adjacent control thermistors (measured at 1-3 seconds), and probably dominated by the 2-second thermistor time constant. We also observed that the zones at either end of the vacuum tank, though locally identical mechanically and in fabrication, had quite different control parameters when tuned properly. This emphasizes the need to retain flexibility in thermal control system design to accommodate the effects of small but important variables in the as-built (versus design) configuration.

The similarity in natural frequency of adjacent control zones gave rise to concern over possible dynamic interaction between zones—oscillatory response of a guard zone could induce a similar oscillation in an inner zone. We tested this by manually varying the setpoint of a guard zone at the observed frequency of the adjacent vacuum-tank zone, and observed no effect. Evidently the combination of conductive damping and integral compensation is adequate to isolate the inner zone. We tested control system performance by observing the amplified

control bridge null signal, the monitor thermistor resistance and the heater output of critical control zones in response to environmental changes. We also looked for correlated changes in maser frequency stability, although this was more difficult because of the known time lag and the presence of small perturbations in frequency from other sources. Our approach to frequency stability measurement was to make an environmental step change on one day and an offsetting change on the succeeding day, and look for a one-day offset response.

SAMPLE PERFORMANCE RESULTS

Figure 4 illustrates an example of performance data recorded over a 2-1/2 day period of laboratory environment changes. Temperature was intentionally allowed to vary over about 10°C. Temperature of the controlled zones is represented by the error signal from each sensor bridge. The mid-plane isolation zone sensor was held to less than 0.01°C with a power change of 60% (we would certainly expect, but expect, but had no sensors to measure, substantial gradients in the mounting plate with such a large power change). The bottom oven and neck guard zones, which control both conductive and radiative losses to the mid-plane zone, were stable to a fraction of a control resolution element (about 0.005°C for the oven, below threshold of measurement for the neck) with 7-9% power change. The adjacent inner tank zone was stable to a few parts in 10^{-5} °C with power variation a little over 1% peak-to-peak. Relative power variations are an indirect measure of the degree to which the critical zones are isolated from the outside environment.

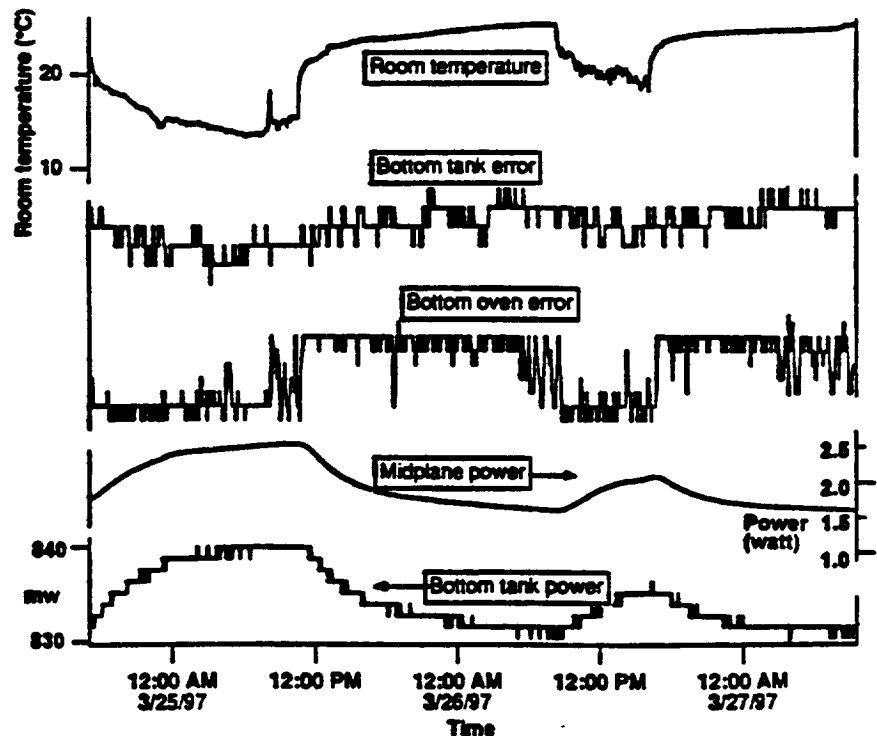


Figure 4. Effects of external environment on control stability

Figure 5 shows performance of an innermost zone when the adjacent guard zone is changed a large amount. For this test the guard zone control set point on the bottom neck was increased by 0.03°C (30X its control band) for about an hour, then returned to its original setting (top trace; discontinuous data shows the digital measurement resolution, trace envelope indicates data noise that changes with sampling period). The bridge error of the guard zone (second trace) shows clearly the settling transients after each adjustment, with a peak-peak amplitude less than 0.01°C . The critical zone is the vacuum tank bottom; its power (third trace) decreases by about 0.3%, roughly the same as the temperature difference between its set point and that of the adjacent guard zone, and shows a 1% spike on resetting. The last trace expands the time scale of the control zone error for the second (resetting) transient, and shows zero offset at ten-microCelsius resolution across the transient. The peak-peak temperature error, noise included, lies within $3 \times 10^{-4}^{\circ}\text{C}$ even while the integral compensation drives the power transient, with a noise-corrected span (dark trace) within a 10^{-4}°C band.

Common-mode effects of electronics unit temperature change are shown in Figure 6. Electronics temperature was abruptly raised by about 10°C and decreased by 15°C two days later. The error signal from an internal tank zone barely shows change at the 10^{-5}°C level, but the indicated temperature measurement from an adjacent sensor appears to change by about 0.05°C , well-correlated in time with electronics unit changes. The monitor circuit is not designed for high-precision measurement but for telemetry over a wide range, and the relative response of the two measurements indicates the degree to which the control system is successfully isolated from common-mode effects.

CONCLUSIONS

The laboratory test program of the HMC has confirmed the ability of the thermal control system to maintain internal zone temperature stability to considerably better than the desired 10^{-4}°C at the control sensors, and to attenuate control power changes, both in the presence of varying environment conditions. Of course, stability of control sensors must be distinguished from overall zone stability. A guard zone power change of 7-9% surely induces some gradients, and a 1% inner-zone power change is a response to this guard-zone

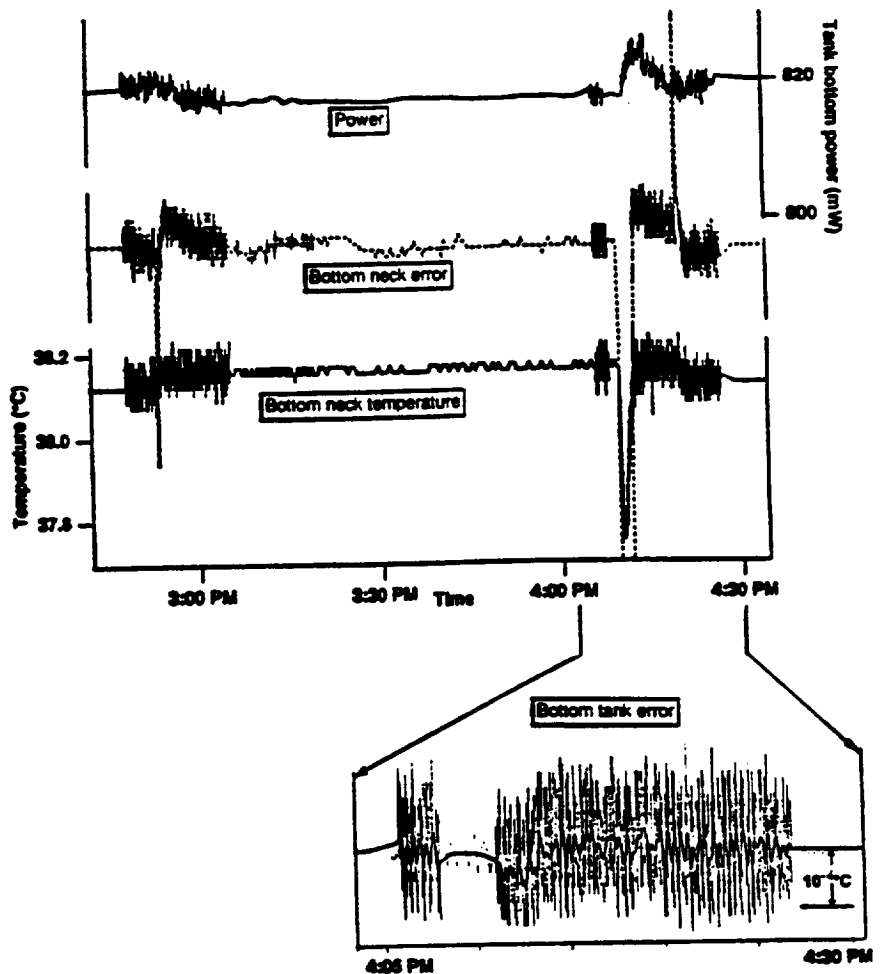


Figure 5. Effect of guard zone on adjacent control zone response

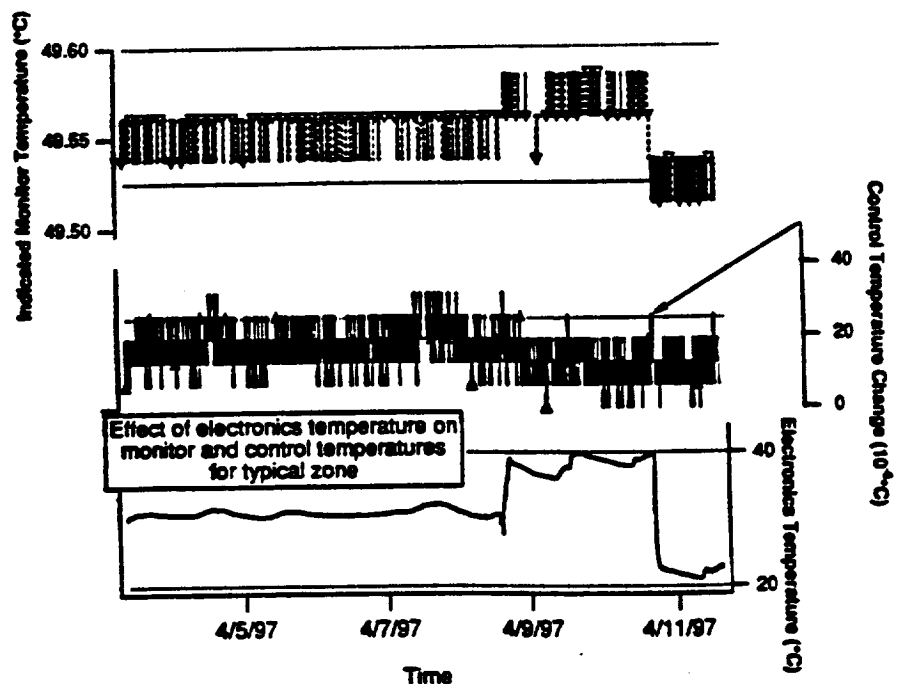


Figure 6. Effect of electronics temperature on monitor and control

non-uniformity. We have also demonstrated successful separation of dynamic response of zones.

The ultimate test of inner-zone control is maser frequency stability. Confirming internal frequency stability has been hampered by unanticipated thermal effects on test cables and other test equipment not part of the flight HMC. Although we can separate these effects from those of internal maser thermal control by the rapidity with which they occur, they introduce enough instability to obscure the desired measurements. This is the focus of ongoing tests.

We have also shown that the discrete nature of micro-processor-based control does not degrade high-stability control performance, and that its advantages in ease of optimizing system performance highly recommend it for such applications.

Long-term stability at the sub-milli-Celsius level is not a design issue for HMC, but might be for another system. We have indicated changes that would enhance long-term stability, and other aging effects would need to receive the same design attention that we have illustrated.

REFERENCES

- [1] Ziegler, J.G., and N.B.Nichols, "Optimum Settings for Automatic Controllers," *Trans. ASME*, V64, No.8, 1942

